NASA/TP—2006–214196

Haughton-Mars Project Expedition 2005
Final Report

Prof. Olivier de Weck & Prof. David Simchi-Levi
Massachusetts Institute of Technology
Kennedy Space Center, Florida

January 2006

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Interplanetary Supply Chain Management & Logistics Architectures

MIT/JPL/USA/PSI

Haughton-Mars Project Expedition 2005

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Interplanetary Supply Chain Management
& Logistics Architectures

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Massachusetts Institute of Technology

Principal Investigators: Prof. Olivier de Weck, Prof. David Simchi-Levi

Sponsor: National Aeronautics and Space Administration (NASA),
Exploration Systems Mission Directorate (ESMD), Exploration Systems Research & Technology (ESR&T) Program, Project (ECP-BAA): ASTP-ASCT-3836

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Figure 1.1: (top) Mars (15S 175E): Gusev Crater, Spirit landing site, source: NASA JPL; (bottom): Earth (75N 90W): Devon Island, Haughton Crater, source: Mars Institute

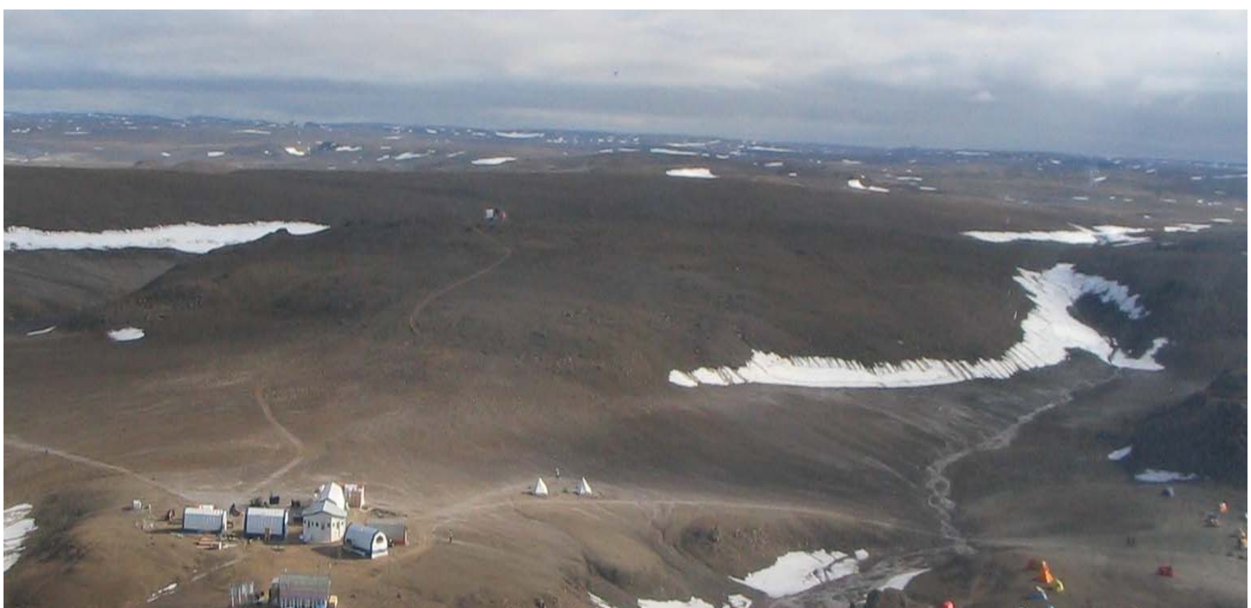

Figure 1.2: Haughton-Mars Project (HMP) Research Station on Devon Island in the high Canadian Arctic. Front left shows the octagonal core and radial modules of the main base with the Arthur C. Clarke Greenhouse. Individual sleeping tents are shown on the right side (front). The satellite communications array is top center (back). The Haughton Crater is in the distant background.

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Executive Summary

The 2005 expedition to the Haughton-Mars Project (HMP) research station on Devon Island was part of a NASA-funded project on Space Logistics. A team of nine researchers from MIT went to the Canadian Arctic to participate in the annual HMP field campaign from July 8 to August 12, 2005. We investigated the applicability of the HMP research station as an analogue for planetary macro- and micro-logistics to the Moon and Mars, and began collecting data for modeling purposes. We also tested new technologies and procedures to enhance the ability of humans and robots to jointly explore remote environments. The expedition had four main objectives. We briefly summarize our key findings in each of these areas.

1. Classes of Supply: First, we wanted to understand what supply items existed at the HMP research station in support of planetary science and exploration research at and around the Haughton Crater. We also wanted to quantify the total amount of imported mass at HMP and compare this with predictions from existing parametric lunar base demand models.

We completed an initial inventory of the HMP research station, totaling over 2300 individual items. The inventory was partitioned into a new functional-based classes of supply (COS) system for exploration logistics, as we discovered that none of the existing schemes, such as the one used for the International Space Station (ISS), were consistent or comprehensive enough. The 10 classes of supply comprise: (1) propellants and fuels, (2) crew provisions, (3) crew operations, (4) maintenance and upkeep, (5) stowage and restraint, (6) exploration and research, (7) waste management and disposal, (8) habitation and infrastructure, (9) transportation and carriers as well as (10) miscellaneous items. This system of classification was validated against the 14 categories of the Cargo Category Allocation Rates Table (CCART) for ISS and through an on-site inventory at HMP. Over the course of the 29-day field campaign we inventoried a total of 20,717 kg, about 46,000 lbs, of supply items. The mass breakdown showed that 45% of the mass was due to transportation vehicles such as all-terrain vehicles (ATVs), 20% were various types of fuels and propellants, 14% were crew provisions (mainly food) and 8% were exploration items and scientific equipment. While we did not capture the mass of the already erected structures, this inventory correlated well with our pre-HMP estimate of 23,740 kg. The inventory was subsequently implemented in an SQL relational database that can be accessed by multiple organizations via the internet. This database captures a total of 50 attributes for each supply class, sub-class and individual item. Customized reports can be easily generated for various users in the supply chain (planners, mission operators, load masters, explorers).

2. **Macro-Logistics Transportation Network**: Our second objective was to understand the nodes, transportation routes, vehicles, capacities and crew and cargo mass flow rates required to support the HMP logistics network.

In all, 56 individuals (scientists and support staff) visited HMP in 2005, producing a total of 683 crew-days on Devon Island, yielding an average stay of 12.2 days. We carefully tracked the flow of cargo and crew, with particular emphasis on the transportation arc between Resolute and HMP. While 19 Twin Otter flights, each with a payload capacity around 2400-2800 lbs, had been originally planned at the beginning of the season, 28 such flights actually occurred. These transported a total crew and cargo mass of 22,750 kg inbound and 12,430 kg outbound. We

found that the inbound capacity utilization of flights was 73%, while the outbound utilization was only 40%. This was primarily so because of ongoing construction activity on base and the asymmetric usage of flights with incoming airplanes being mainly empty on the return flight during the first half of the season. Our analysis suggests ways in which flights can be used more effectively, primarily by smoothing the campaign schedule, more carefully planning and staging of cargo at Resolute and through establishment of a formal reverse logistics staging area on Devon Island. However, we also found that apriori optimized flight schedules are easily rendered obsolete due to the uncertainties of the Arctic environment including the weather, competing demands for airplanes from other field parties, and medical emergencies.

3. Agent and Asset Tracking: Since the current inventory management system on ISS relies heavily on barcodes and manual tracking, we wanted to test new automated technologies and procedures such as radio frequency identification (RFID) to support exploration logistics.

To this end we conducted a set of both formal and informal RFID experiments at HMP and found that electronic tagging of supply items, people and vehicles on a research base opens up entirely new ways of managing inventory, understanding usage patterns in real-time and enhancing exploration planning and analysis capabilities. A formal RFID gate experiment in the MIT tent showed that RFID can save a factor of 2-3 in inventory management time. However, the accuracy of recording transactions with RFID was only between 70-85%. The main technical problems involved optimal antenna installation, as well as tagging of metallic items and objects containing liquids. RF interference issues in the 915 MHz and the 2450 MHz bands occurred with other equipment on base and demonstrated that future distributed sensing systems will have to be designed as an integral part of vehicles and habitats, rather than retrofitted as an afterthought. We also demonstrated new uses of the technology such as monitoring of personnel movements between modules, and ATV usage around the base. The expedition stimulated follow-on research on new applications, such as “smart cabinets” that are self-aware and can sense their own contents, as well as “fast checkout” of exploration vehicles with the help of handheld readers.

4**. Micro-Logistics (EVA):** Finally, we wanted to understand the micro-logistical requirements of conducting both short (<1 day) and long traverses in the Mars-analog terrain on Devon Island. Micro-logistics involves the movement of surface vehicles, people and supplies from base to various exploration sites over short distances (<100 km).

At HMP we developed a standardized way of recording objectives, parameters and constraints for Extravehicular Activities (EVA) suitable for surface exploration. We applied this methodology to document a total of 8 traverses. On each traverse three main classes of items were brought along: consumables (e.g. water), safety equipment (e.g. UHF radios) and research equipment (e.g. cameras, rock hammers). More importantly, we found that none of the EVAs were conducted exactly as planned, primarily due to impassability of the originally planned path. Therefore, real-time re-planning tools and new surface mobility strategies and vehicles, such as an ATV-towed planetary camper, should be high priority initiatives in this area.

Conclusions: Our main conclusion from the 2005 expedition is that the HMP research station is indeed quite analogous to a Moon and Mars exploration base in some regards. Logistics

involving surface transportation in and around base, equipment for scientific research (mainly planetary geology) at the Haughton Crater, field- and telemedicine, the autonomous greenhouse as well as the satellite communications and computational infrastructure map well to the parametric models we have developed for space exploration logistics requirements. Other aspects, however, primarily those involving human habitation, food and the abundance of water are clearly not analogous. Other significant differences are relatively frequent opportunities for resupply, and generous stowage space at HMP. This report provides details regarding areas were logistical lessons and data were obtained, and where further research is needed.

Recommendations: Our recommendations for HMP logistics, specifically, center on creating a more formal estimation and planning process for crew and cargo. This could be achieved by smoothing the campaign schedule, more strongly emphasizing reverse logistics between HMP and Resolute, and creating a longer term funding, transportation and warehousing plan with a planning horizon beyond a single season. A safety-critical item at HMP is the relatively informal way in which various fuels and propellants are managed, stored and marked. The biggest uncertainty remains around actual water usage.

Recommendations for NASA Exploration logistics focus on the creation of a web-based, unified, relational logistics information architecture based on a functional supply classification. We believe that this has the potential to avoid many current concerns in the future. Further research into RFID and other distributed sensing technologies and their integration into vehicle and habitat design is critical. The need to have real-time knowledge of locations and status of agents and assets at both orbital and surface nodes on the Moon and Mars will be of critical importance to both ensure safety, avoid shortages and improve operational efficiency.

From an exploration perspective we found that HMP– despite the identified differences with a Lunar or Martian base – is an ideal research environment for interplanetary logistics, because it:

- represents a “semi-closed” system similar to a Moon/Mars base
- features a rich, yet manageable, set of agents (crew), supply items and vehicles
- is subject to a thin, uncertain supply line, and extreme environmental conditions
- provides natural usage patterns to analyze the movement of crew and cargo in the context of a planetary-analog research base on Earth

Future research at HMP will involve refinement of the current inventory, expansion of the HMP supply chain network model beyond the arc between Resolute and HMP, comprehensive RFID tagging, reading and automated database management as well as documenting EVA logistics requirements for overnight traverses, with the possibility of air-dropping caches at optimal locations in the Haughton Crater. Related research activities will include new surface mobility architectures, spacesuit experiments and the use of autonomous rovers as scouts.

Participants of the 2005 MIT-HMP Expedition:

Prof. Olivier de Weck (lead), Prof. Jeffrey Hoffman, Jaemyung Ahn, Julie Arnold, Erica Gralla, Xin (Mike) Li, Jessica Marquez, Sarah Shull, Matthew Silver

Cambridge, January 1, 2006

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Acknowledgments

First, and foremost we thank our sponsor, NASA, for funding this expedition. The MIT HMP 2005 expedition – as an integral part of the larger research project - would not have happened without our Contracting Officer's Technical Representative (COTR), Dr. Martin Steele, at the NASA Kennedy Space Center. The original project proposal contained field research in Antarctica and observation of logistics for remote oil & gas exploration platforms. However, after learning that Antarctic logistics are already very well established, and that long waiting lists and approvals have to be obtained from NSF to visit Antarctica, we proposed to analyze HMP's Arctic logistics instead of the original plan. Dr. Steele, along with Emily Unbehaun, our NASA contracting officer, had the vision to go along with the new plan.

Dr. Pascal Lee (Mars Institute, SETI Institute) visited MIT in March of 2005 and we first learned about the potential of the HMP project to serve as an analog site on Earth to study Mars (and Lunar) exploration activities and logistics. Dr. Lee has been very supportive of our project and spent significant time with our team, sharing past experiences with HMP logistics as well as his thoughts and data on current operations. Our thanks go to him for his support and endurance.

Along with Dr. Lee we want to thank other members of the HMP team such as Dr. Stephen Braham (Mars Institute, Simon Fraser U.) for communications support and RFID suggestions, John Schutt, the base camp manager, for keeping operations safe and cooperating with us during the data collection and RFID testing phase and Ms. A.C. Hitch for her skills, endurance and experience in field construction and carpentry of the MIT tent. Jack Brezina, the camp cook, kept us well fed and taught us the importance of proper nutrition and the social aspects of meals during exploration far from home. Dr. Gordon Osinski (Canadian Space Agency (CSA)) assisted with construction, and accompanied us on initial field explorations. Dr. Alain Berinstain (CSA, U. of Guelph), shared the entire greenhouse inventory with us and provided the vision for a larger scale "network of analog sites". Dr. Jean-Marc Comptois MD, Chief Flight Surgeon of the CSA, shared his views and inventory for field expeditionary medicine and telemedicine.

Afreen Siddiqi at MIT conducted the research into functional classes of supply presented in Appendix B, and developed the initial model of planetary base logistics mass and volume requirements (Appendix D). We also thank Julie Finn at MIT who organized our travel logistics, skillfully navigating an administrative obstacle course both within and outside MIT. Angela Olsen diligently managed our finances and tolerated our unusual purchasing requests. Our co-investigators back South included Joe Parrish (Payload Systems Inc.), Dr. Robert Shishko (JPL) and Mr. Andy Evans (United Space Alliance) and the remainder of the ISCMLA team. Lukas of the Qausuittuq Inns North in Resolute, the last outpost before Devon Island, taught us about Inuit hospitability, and Rozanne Amelotte at First Air was helpful in lining up our travel to Resolute. Finally, our thanks go to the unnamed staff and pilots at the Canadian Polar Continental Shelf Project (PCSP) and Kenn Borek Air Ltd. for providing reliable logistics and safe passage.

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1 Motivation

A vast number of scientific principles and techniques have been developed since World-War-II to improve the effectiveness and efficiency of terrestrial supply-chains in the private and military sectors. The potential benefits of this body-of-knowledge are currently only poorly understood in the context of space exploration. Sustainable space exploration, however, is impossible without appropriate supply-chain management (SCM). Unlike Apollo, future exploration will have to rely on a complex supply-chain network on the ground *and* in space. The primary goal of the Interplanetary Supply Chain project is therefore to develop a comprehensive SCM framework and planning tool for space-logistics, which is a critical gap in needed capabilities.[1]

As part of the NASA sponsored research project on Interplanetary Supply Chain Management and Logistics Architectures we are developing an integrated space-logistics framework in four steps. The first of these steps is a critical look at terrestrial supply chain analogies and what we might learn from them for space exploration. The proposal reads:

"We are investigating and contrasting lessons learned from SCM in (i) major industries specialized in "low-quantity", capital-intensive products, (ii) long-range military operations such as aircraft and naval-submarine logistics, and (iii) supply-chains for operations in remote environments, specifically the NASA sponsored Haughton-Mars Project (HMP), which is being developed into the functional equivalent of a Moon or Mars exploration outpost in the high Arctic (75N 90W). This will provide initial class-of-supply and traverse logistics information for modeling purposes. We will also identify where terrestrial logistics analogies break down, when applied to space exploration."

Within the work on terrestrial analogies, this report summarizes the results of (iii)[2], i.e. the results obtained from an expedition to the HMP Research Station (HMP RS) which was conducted in July and August 2005. A team of researchers from the MIT Department of Aeronautics and Astronautics, the Department of Civil and Environmental Engineering and the Engineering Systems Division conducted a field expedition to the remote Haughton-Mars Project research base, a few hundred miles from the magnetic North Pole. The central goal for the arctic field season, which lasted from July 8 to August 12, 2005, was to investigate the similarities between logistics for remote terrestrial sites and supply chains for future planetary Moon and Mars exploration for modeling purposes. Another objective was to deploy and test technologies such as Radio Frequency Identification (RFID) for remote base operations.

The MIT team conducted this research in cooperation with the Haughton-Mars Project[3], an international interdisciplinary field research project supported by NASA and the Canadian Space Agency (CSA) and managed by the Mars Institute and the SETI Institute. The HMP project is led by Dr. Pascal Lee and Dr. Stephen Braham.

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[1] See reference [1], Section 7, p.33.
[2] Statement of Work, Work Breakdown Structure, WBS 2.3
[3] <http://www.marsonearth.org>

Exploration activities at the site are driven by the scientific study of the 38 million year old Haughton impact crater and surrounding terrain on Devon Island. At 75 degrees North latitude, Devon Island is a high arctic desert and the largest completely uninhabited island on Earth. The site was chosen both for its scientific relevance to planetary surface studies and its operational similarity to aspects of lunar and Martian terrains.

While no environment on Earth is exactly like that of the Moon or Mars, the Haughton site offers a unique combination rocky desert terrain in the context of a large impact crater, a wide variety of planetary-relevant terrains, and from an operational standpoint, relative isolation, remoteness, and logistical challenges by terrestrial standards. With regards to Mars specifically, the site combines attributes of a cold-climate desert, pervasive permafrost and ground ice, a wide range of geologic formations that are at least morphologic analogs to several classes of Martian surface features, and many examples of adaptations of microbial life to extreme environments.

The HMP science program has over the years helped further our understanding of the history of water and of past climates on Mars, the effects of impacts on Earth and other planets, and the possibilities and limits for life in remote environments. With regards to the Moon, important lessons regarding planetary impact processes[4], ground-ice drilling and exploration in regolith-like materials (e.g., DAME Project funded by NASA MIDP), and overall surface exploration operations (e.g., Carnegie Mellon University's sun-synchronous Hyperion rover field tests funded by NASA) have also been gained in the past.

[4] See upcoming special issue of *Meteoritics & Planetary Science* on HMP Science Results, Dec 2005

2 Introduction

2.1 Objectives

The objectives for the MIT HMP 2005 Expedition were defined as follows:

1. Catalogue classes and sub-classes of supply in the field
2. Create and quantify an initial network model of the HMP supply chain
3. Conduct field experiments with RFID tagging, reading and automated database management to facilitate tracking of agents (people), supply items and vehicles
4. Establish logistics requirements for EVAs, including short traverses and longer excursions with overnight stays away from the HMP RS.

Aside from the classes of supply database, we planned to release a report containing field observations from HMP exploration logistics and recommendations for analogies between HMP and potential lunar and Martian destinations. This is the purpose of the present report.

2.2 Description of the HMP Project

The Haughton-Mars Project (HMP) is an international, multidisciplinary, scientific field research project centered on the exploration of the Haughton impact crater site on Devon Island, Nunavut, High Arctic, viewed as an analogue for Mars. The HMP research program has two components: Science and Exploration. The HMP Science Program includes investigations in planetary sciences, geology, astrobiology, microbiology, and environmental sciences, and is aimed at advancing our understanding of the formation and evolution of the Earth and other planets, the adaptations of life in extreme environments, and the possibilities and limits of life elsewhere in the universe. The HMP Exploration Program focuses on advancing the development of new technologies and operational strategies for the future exploration of the Moon, Mars, and other planetary bodies by robotic systems and humans.

The HMP was established in 1997 by Dr. Pascal Lee as a small pilot study with initial support from NASA, the U.S. National Research Council (NRC), and the Geological Survey of Canada. Based at NASA Ames Research Center, the project has grown over the years to become the largest, most integrated, planetary analogue field research program in the world. The HMP now hosts up to sixty field participants each year and represents the research interests of a consortium of international partners including government agencies from the United States and Canada, as well as private organizations, academic institutions (including MIT), industrial partners, and non-profit groups. Funding for the HMP's research program is provided mainly by NASA and the Canadian Space Agency. The project is managed jointly by the Mars Institute and the SETI Institute, in collaboration with Simon Fraser University (BC, Canada). The Mars Institute manages and operates the HMP Research Station (HMP RS).[5]

[5] For more information, see: <**www.marsonearth.org**>

Figure 2.1: The high Canadian Artic, with Resolute on Cornwallis Island and Devon Island indicated. Researchers stop over in Resolute on the way to the HMP research station on Devon Island (75°N 90°W). Resolute serves as a logistics base for Devon Island.

Beyond basic science, the remote HMP research station functions as an analogue planetary base, supporting a diverse array of exploration technology and engineering test projects that also benefit from the Moon/Mars-analog terrain, remoteness, and exploration-like activities undertaken by geologists, microbiologists, and other researchers. For example, over the past several years, the Canadian Space Agency has been a primary developer and user of the HMP Arthur C. Clarke Greenhouse with the goal of designing and testing autonomous and remote-controlled operations of a greenhouse and plant-growth technologies in remote environments.[6] Hamilton-Sundstrand, an aerospace engineering firm headquartered in Connecticut and a division of United Technologies, has been collaborating with the HMP since 2000 to develop and test advanced space suit and EVA systems designs by allowing field exploration activities to serve as an operational requirements driver[7]. Also, this year the Drilling Automation for Moon/Mars Exploration (DAME) activity, a project funded by NASA's Mars Instrument Development Program (MIDP) and lead from NASA Ames Research Center, tested autonomous

[6] Point of contact at CSA: Dr. Alain Berinstain
[7] Point of contact at Hamilton Sundstrand: Ed Hodgson

fault diagnosis and artificial intelligence software on a prototype Moon/Mars drill. Many other exploration technologies and prototypes have been tested at Haughton under the auspices of the HMP since 1997.

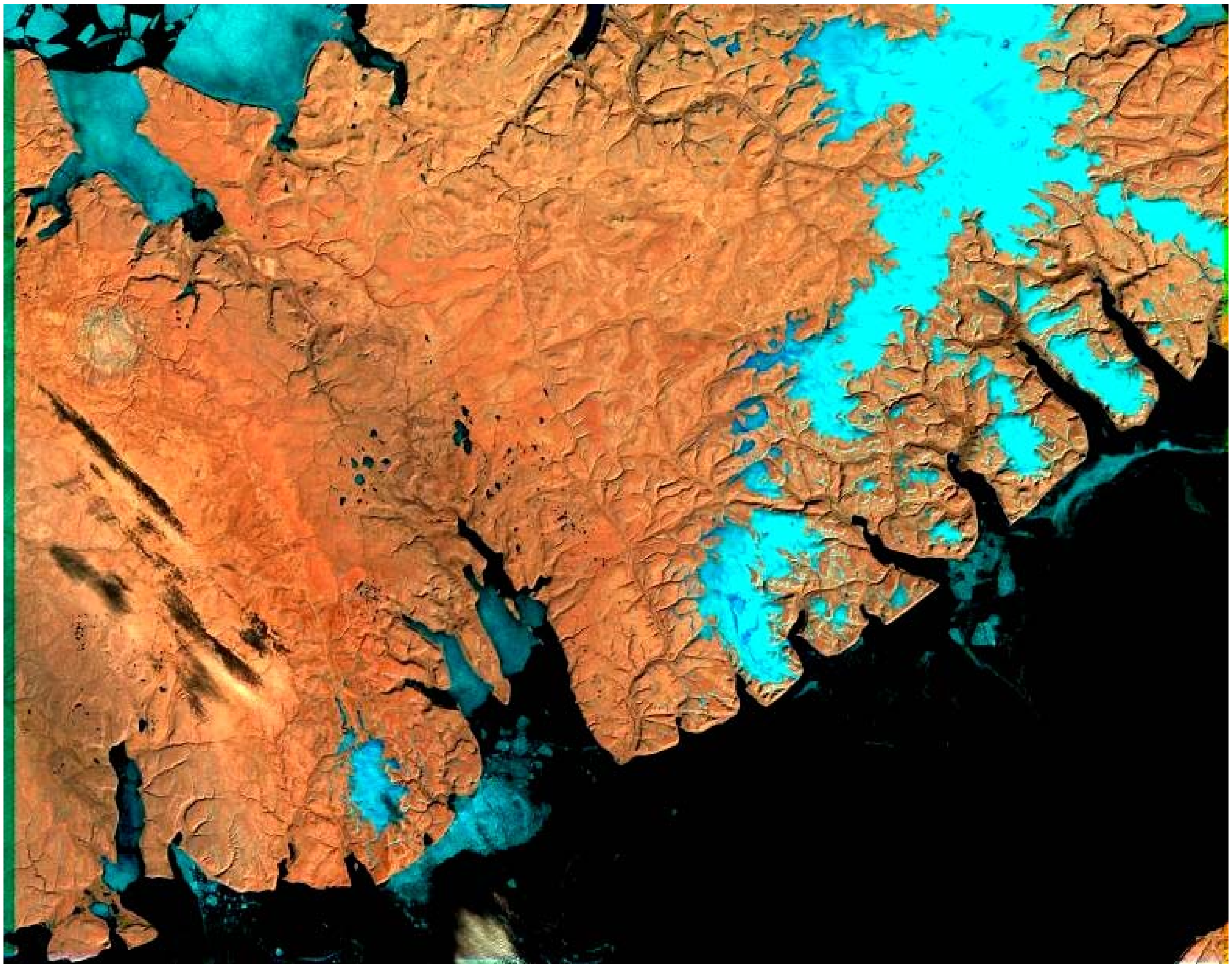

Figure 2.2: Landsat image of the central portion of Devon Island. The scene is approximately 240 km wide. The Haughton crater can be seen as a circular structure in the upper left corner (20 km diameter), source: NOAA

The HMP Research Station itself, or HMP *base camp*, has also grown, and now includes a large mess tent (48 ft long)[8], a computing & communications or *Systems* tent, a large project office and laboratory tent for general work, several peripheral lab tents, a greenhouse test bed, and an octagonal central module or *Core* which will eventually unite the buildings into a single star-shaped structure. There are also thirteen all terrain vehicles (ATVs), a HUMVEE outfitted for longer traverses (the Mars Institute's "MARS-1" HUMVEE Rover), and a small airstrip to support Twin Otter airplane flights in and out of base. This year, an MIT tent was established for the space logistics project and also in preparation for future MIT involvement at the site. As a whole, the base can currently accommodate a maximum of about forty people at a given time,

[8] These "tents" are semi-permanent structures with wooden floors, metal lattice frames and synthetic water-proof tarps as covers. They are anchored to the ground, but can be disassembled and moved if needed.

with researchers sleeping in individual personal tents a short distance away (100 m) from the main structures (see also Fig. 1.2).

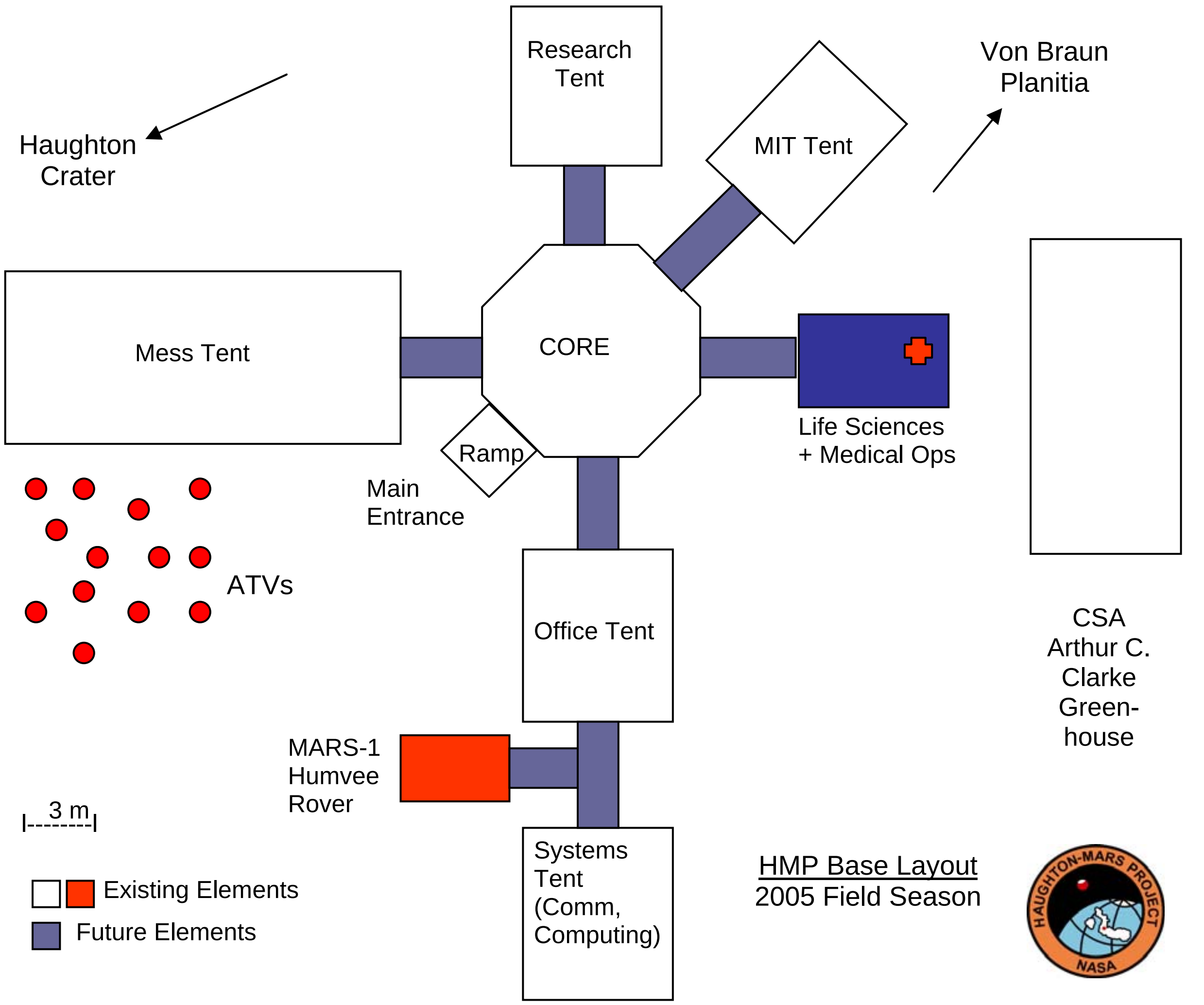

Figure 2.3: Current Layout of HMP Research Station on Devon Island

While a typical field season at HMP witnesses multiple groups of researchers interspersed throughout the roughly 4-6 weeks, a core group of researchers and base camp managers ensures the day to day operations. As project lead and principal investigator, Dr. Pascal Lee and core HMP collaborators are currently responsible for a large amount of pre-planning, field research, and operations. This includes everything from creating a workable field season schedule and running daily meetings at camp, to negotiating land access for research with the local Inuit community.[9] Significant to our project, Dr. Lee has also been the main logistics planner for HMP. As elaborated below, this involves coordinating multiple streams of research equipment, base supplies, and personnel from various parts of world into Resolute and eventually to camp.

[9] Since 1999, when the territory of Nunavut was split off from the Northwest Territories (NWT), there is a distinction between Inuit-owned land and "crown" land, which is owned by the Canadian government.

Most often, once supplies reach Resolute, they are shipped via Twin Otter airplane chartered via the Polar Continental Shelf Project (PCSP), a Canadian Government Arctic science logistics support program. Dr. Lee secures annual logistical support from PCSP to support the HMP field campaign. In some instances, however, HMP supplies have been flown directly from the United States to the Arctic with optional air-drops on Devon Island through interagency agreements between the NASA HMP and the United States Marine Corps (typically using C-130 airplanes).

Other core members of the HMP team include Dr. Stephen Braham, Mr. John Schutt and, not insignificantly, the camp's cook. Dr. Braham runs the communication systems at the base, including the internet link, safety radios, short-wave radio to Resolute, and any other form of RF communications. This constitutes part of Dr. Braham's research in field communications, computing, and networking systems in support of advanced planetary human and robotic exploration missions as well as disaster relief. Dr. Braham is aided in his duties by a team he brings from Simon Fraser University (Vancouver, Canada). Dr. Schutt is the HMP RS Base Camp Manager, responsible for all aspects of daily operations such as power supply, ATV management, waste management, tent maintenance, and other critical activities. He has tremendous experience in remote environments, having spent many summers in Antarctica searching for meteorites, and having run HMP since its inception. Mr. Schutt and the camp cook typically work with other team members hired from the local communities of Resolute Bay or Grise Fjord to help in their duties.

Because groups of researchers come and go throughout the field season, but also because the High Arctic is an unforgiving environment, many aspects of camp life are closely regulated. Safety is a very high priority, and all researchers receive a safety briefing upon arrival. Because of the difficulty in searching the remote terrain, participants are never allowed to walk outside of the main camp area without at least one other participant. Polar bears are also a concern, and all camp members are trained to use shot-guns in the case of an emergency. Safety radios must be taken on any traverse. Some aspects of these issues, in fact, are pertinent to all forms of exploration. Some questions, such as "what is the minimum number of people for a long-range ATV traverse," are analogous to lunar and Mars exploration from a safety perspective.

In addition to safety concerns, there is an effort to maintain a sense of community throughout the season. Meetings are held every morning and every evening at fixed times to keep all participants updated on various activities, and research presentations are often given after dinner. This effort is actually rather important, for the isolation and harshness of the environment are often psychologically difficult. Approximately 11 research projects were undertaken at HMP this year, ranging from multi-person efforts to single-person scientific investigations. MIT sent a total of nine researchers interspersed throughout the season. Appendix J contains a set of short biographies of the MIT participants and summarizes how each researcher contributed to the overall effort.

Table 2.1 shows an excerpt from the HMP 2005 planning schedule. This does not reflect the arrivals and departures of personnel that actually occurred (see Section 4.2 for such data), but it is a close approximation. The rows represent the days of the field season, while the columns show the presence of individuals at HMP, color-coded by organization and research project.

The information shows that the field season started with a core team of roughly 10 individuals in early July, peaked near 40 in late July, and ended again with roughly 10 individuals for camp closing in mid-August. This schedule is perhaps the most important planning document for HMP, as logistics requirements in terms of crew consumables, research equipment and the flight schedule are derived from it.[10]

Table 2.1: HMP 2005 unofficial field schedule (excerpt), MIT team in grey

HMP-2005 DATE	LEE, Pascal	SCHUTT, John	BREZINA, Jack	BRAHAM, Steve	SFU-2	BERINSTAIN, Alain	OSINSKI, Gordon	BAMSEY, Matt	GIROUX, Richard	GRAHAM, Tom	LEVEILLE, Richard	SFU-3	DEPUTY	DE WECK, Olivier	GRALLA, Erica	SILVER, Matt	LI, Mike	AHN, Jaemyung	SHULL, Sarah	ARNOLD, Julie	MARQUEZ, Jessica	HOFFMAN, Jeffrey	GLASS, Brian	CANNON, Howard	DAVIS, Kiel	CALHOUN, Gale	HANAGUD, Sathya	RUZZENE, Massimo	McBRIDE, Karin	HS1	HS2	RUNCO, Mario	FERRIS, John	JONES, Jeff	JSC-2	BOUCHER, Marc	THATER, Hans	DISCOVERY CANADA	TOTAL HMP ON DEVON	HMP-2005 DATE
Jul 06 We																																							0	Jul 06 We
Jul 07 Th																																							0	Jul 07 Th
Jul 08 Fr																																							0	Jul 08 Fr
Jul 09 Sa																																							0	Jul 09 Sa
Jul 10 Su	1	1	1			1	1						1	1	1	1	1																1						11	Jul 10 Su
Jul 11 Mo	1	1	1			1	1						1	1	1	1	1																1						11	Jul 11 Mo
Jul 12 Tu	1	1	1	1	1	1	1	1	1	1			1	1	1	1	1																1						16	Jul 12 Tu
Jul 13 We	1	1	1	1	1	1	1	1	1	1			1	1	1	1	1																1						16	Jul 13 We
Jul 14 Th	1	1	1	1	1	1	1	1	1	1			1	1	1	1	1																1						18	Jul 14 Th
Jul 15 Fr	1	1	1	1	1	1	1	1	1	1			1		1	1	1																1						17	Jul 15 Fr
Jul 16 Sa	1	1	1	1	1	1	1	1	1	1	1		1		1	1	1																1						18	Jul 16 Sa
Jul 17 Su	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1						1	1	1	1	1	1					1			1			26	Jul 17 Su
Jul 18 Mo	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1						1	1	1	1	1	1					1			1			26	Jul 18 Mo
Jul 19 Tu	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1						1	1	1	1	1	1					1			1			25	Jul 19 Tu
Jul 20 We	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1						1	1	1	1	1	1					1			1			25	Jul 20 We
Jul 21 Th	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1	1	1				1	1	1	1	1	1	1				1			1			31	Jul 21 Th
Jul 22 Fr	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1	1	1				1	1	1	1	1	1	1				1			1			31	Jul 22 Fr
Jul 23 Sa	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1	1	1				1	1	1	1	1	1	1				1			1			31	Jul 23 Sa
Jul 24 Su	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1	1	1				1	1	1	1	1	1	1				1	1		1		4	36	Jul 24 Su
Jul 25 Mo	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1	1	1				1	1	1	1	1	1	1				1	1		1		4	36	Jul 25 Mo
Jul 26 Tu	1	1	1	1	1							1	1					1	1				1											1		1		4	21	Jul 26 Tu
Jul 27 We	1	1	1	1	1							1	1					1	1				1											1		1		4	21	Jul 27 We
Jul 28 Th	1	1	1	1	1							1	1					1	1	1	1		1							1	1			1		1		4	25	Jul 28 Th
Jul 29 Fr	1	1	1	1	1							1	1						1	1	1									1	1			1					18	Jul 29 Fr
Jul 30 Sa	1	1	1	1	1							1	1						1	1	1									1	1			1					18	Jul 30 Sa
Jul 31 Su	1	1	1	1	1							1	1						1	1	1	1								1	1	1		1	1				24	Jul 31 Su
Aug 01 Mo	1	1	1	1	1							1	1						1	1	1	1								1	1	1		1	1				24	Aug 01 Mo
Aug 02 Tu	1	1	1	1	1							1	1							1	1	1								1	1	1			1				17	Aug 02 Tu
Aug 03 We	1	1	1	1	1							1	1							1	1	1								1	1	1			1				17	Aug 03 We
Aug 04 Th	1	1	1	1	1							1	1							1	1	1								1	1	1			1				17	Aug 04 Th
Aug 05 Fr	1	1	1	1	1							1	1							1	1	1								1	1	1			1				17	Aug 05 Fr
Aug 06 Sa	1	1	1	1	1							1	1							1	1	1								1	1	1			1				17	Aug 06 Sa
Aug 07 Su	1	1	1	1	1							1	1							1	1	1								1	1	1			1				17	Aug 07 Su
Aug 08 Mo	1	1	1	1	1							1	1							1	1	1								1	1	1			1				17	Aug 08 Mo
Aug 09 Tu	1	1	1	1	1							1	1																										9	Aug 09 Tu
Aug 10 We	1	1	1	1	1							1	1																										9	Aug 10 We
Aug 11 Th	1	1	1	1	1							1	1																										9	Aug 11 Th
Aug 12 Fr																																							0	Aug 12 Fr
Aug 13 Sa																																							0	Aug 13 Sa
																																							0	
TOTALS	33	33		31	31	16		14	14	14	10			5	9	16	16	8	12	12	12	9	12	9	9	9	9	9		12	12		16		9	12		20	671	TWIN RTS

- Project Core Scientists and Staff
- Student Field Assistants from Resolute Bay and Grise Fiord
- Geology & Geophysics (U. of Paris)
- Geology & Geochemistry (U. Aberdeen)
- Greenhouse (U. of Guelph + CSA)
- Interplanetary Exploration Logistics and EVA (MIT)
- Robotics & Automation: DAME Soil Sampler (NASA ARC + JSC + Honeybee Robotics + NASA HQ)
- Human Exploration: Spacesuit (Hamilton Sundstrand)
- Human Exploration: (NASA JSC)
- Human Exploration: Flight Surgeons Med Ops & Research
- Education/Public Outreach

[10] See Sections 4.2 and 4.4 for further details on logistics and flight requirements derived from this schedule.

2.3 Climate, History, and Culture in the Arctic

HMP is located on Devon Island, which is part of the territory of Nunavut, in the Canadian Arctic. This section provides some context for the "remote" character of the HMP research station by describing the climate, history, and culture of the region. While only the climate and geology of Nunavut have a direct impact on the HMP, the history and culture of the region affect the operation of the base in significant ways. For example, much of the Haughton Crater is Inuit-owned land, and permission must be sought from Inuit authorities in order to do scientific work there. An understanding of the Inuit culture is essential in seeking and acquiring such permission.

The climate of Nunavut is one of the harshest on Earth. The Arctic winter averages about minus 28 degrees Celsius, warming in the summer to just between 5-10 degrees Celsius. Most of the territory of Nunavut is composed of polar desert, with an average of less than 100 mm of rain or snow a year. In the high Arctic (including Devon Island), the land is often barren, with animal and plant life existing only on the coasts and in scattered outcrops where organic waste has been deposited. Arctic poppies and other small plants crop up where animals have died or humans have once lived, but the rest of the land is rocky and barren (see Figure 2.4). Polar bears and people hunt for food along the shores, where fish, seals, and land-based animals can be found [2].

Figure 2.4: Arctic poppies

The Inuit people are the aboriginal inhabitants of the North American Arctic territories. Until recently, they were labeled "Eskimos" by outsiders, but they prefer the name "Inuit" which means simply "the people" in their language of Inuktitut. The origins of the Inuit probably trace back to Alaska, where their coast-dwelling ancestors hunted seals, whales, and caribou. About a thousand years ago, they began to spread farther East, replacing another group known as the Tunit (also referred to as the now extinct Thule Civilization). Parts of some Tunit dwellings survive today; our expedition photographed one such site (see Figure 2.5); the bones would be covered with skins to keep the heat in. The Inuit and Tunit developed ingenious methods of adapting to their harsh environment: note how the entrance to the dwelling is low to the ground, so that warm air produced inside the dwelling rises to the ceiling and does not escape out the entrance.

Figure 2.5: Ancient Tunit dwelling. Resolute Bay, Nunavut, CA.

The arrival of outside explorers caused a host of problems for the Inuit starting in the 19th century, including competition in whaling, and especially infectious diseases. It was not until after the Second World War that the Canadian government took an interest in the downtrodden state of the Inuit people. In order to distribute services and welfare, the government began to resettle large numbers of Inuit into permanent communities, causing them to abandon their traditional nomadic lifestyle. This caused increased dependence on government jobs and welfare, because few other economic opportunities existed. Hunting restrictions have also contributed to the loss of the traditional Inuit way of life and have in part caused a sometimes tense relationship between local Inuit communities and the Canadian government [3].

Today, most of the Inuit live in the Canadian territory of Nunavut, made up of large former portions of the Northwest Territories (NWT). The word “Nunavut” means simply “our land,” an appropriate label for an area that has been home to the Inuit for centuries. Nunavut was established through the initiative of the Inuit people. An Inuit organization’s study of land use staked out Inuit claims to Arctic land in 1973. This study set in motion a long process that ultimately led to the creation of the Nunavut Territory and Government on April 1, 1999. The new government faces a large set of unique challenges in bringing oversight and services to its far-flung population. The territory extends through two million square kilometers of Canada, with a total population of 29,300 (2004) and density of roughly one person per 70 square kilometers. Nunavut’s communities vary in population from 25 up to 6,000 in Iqaluit, the capital. None of Nunavut’s communities are connected by road or rail to any other communities, so everything must be shipped by air or by sea; this requirement results in high costs of living. The northernmost community is Grise Fjord, at 78N; Resolute Bay (our point of access for Devon Island) is only slightly farther south, with a population of about 200. Nunavut’s leaders are making strides toward creating a government specially suited to this far-flung people and their challenging environment by decentralizing government in order to bring it closer to the people, and researching services such as telemedicine that can broaden the reach of government services. It is hoped that the Inuit economy, culture, and ties to the land can be revitalized with the new territory and government [4]. Appendix A has a list of facts on Nunavut, HMP and its context.

2.4 Devon Island

Devon Island (Fig. 2.1, 2.2) is the largest uninhabited island on Earth, with a surface area of approximately 60,000 km^2. Its geology presents two major provinces: a thick (presently ~ 1.3 km) subhorizontal sequence of Paleozoic (Cambrian to Devonian) marine sedimentary rocks dominated by carbonates (dolomite and limestone) forming part of the Arctic Platform; and a Precambrian crystalline (gneissic) basement lying unconformably under the stack of marine sediments, forming part of the Canadian Shield. The Paleozoic sediments present a gentle dip of approximately 4° towards the west. The flat-topped plateau characterizing much of Devon Island's surface is an old erosional surface (peneplain) exposing sediments of increasing age towards the east. The coastal areas of the island present steep sea cliffs and deep glacial trough valleys and fjords (Appendix I), many of which were likely last occupied by ice during the Last Glacial Maximum which ended approximately 10,000 to 8,000 years ago. A substantial ice cap representing a remnant of the Laurentide/Inuitian ice sheet system still occupies the easternmost third of the island. The rest of Devon Island presents a barren rocky surface incised by sinuous glacial trough valleys, dendritic meltwater channel networks, and clusters of small lakes [5].

3 Inventory and Classes of Supply

3.1 Functional Classes of Supply for Exploration

The first objective of the expedition was to understand what supply items exist at the HMP research station in support of planetary science and exploration research. We also wanted to quantify the total amount of imported mass at HMP and compare this with predictions from existing parametric lunar base demand models.

A new formulation of Classes of Supply (COS) was required due to the non-existence of any scheme that would have been suitable for interplanetary exploration logistics. The COS of several organizations that carry out extensive logistical operations in remote locations such as NATO, the U.S. Military, and NASA (for ISS) were initially analyzed to determine if any would be suitable for our use. It was found that the classification schemes employed by those organizations did not have a uniform way of categorizing the items in the supply chain, and were customized for their particular needs. Even the most closely related COS, the Cargo Category Allocation Rates Table (CCART) used for ISS, had several deficiencies when exploration logistics in a larger context were considered. For instance, there are no categories in CCART that would allow for classifying propellants, habitation infrastructure, or surface exploration equipment. Appendix B provides details on our COS comparative analysis.

A new function-based generic COS classification was therefore formulated (Fig. 3.1) that would serve the requirements of an interplanetary exploration supply chain. The processes (functions) involved in an exploration enterprise were first identified, followed by their associated objects.

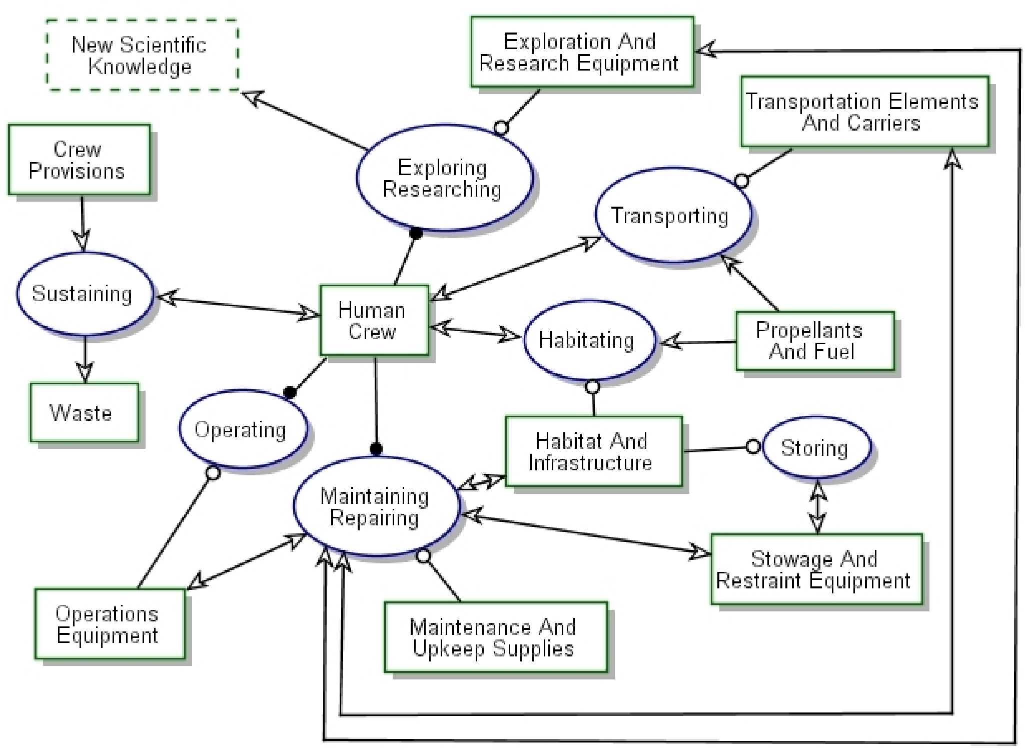

Figure 3.1 Object-Process Diagram [6] of a generic Exploration System

In Figure 3.1 ovals represent processes (functions), while rectangles identify objects. Objects and processes are linked via affectee, consumee, resultee, and agent or instrument links [6]. Specifically, the human crew explores and researches sites of interest to generate new scientific knowledge[11]. This requires that the crew be transported there with transportation elements (vehicles and carriers), which causes consumption of propellants and fuels. Exploration and research equipment facilitates the process of exploring and researching. During the entire time the human crew must be sustained with various crew provisions (water, gases, food, medical supplies…) which produces waste. For longer durations the crew must be sheltered in a habitat or larger ground infrastructure which often also consumes energy in the form of fuel. Inside this infrastructure provisions must be made for stowage/storage and restraint of various supply items. Operations equipment is required to allow the crew to communicate with the outside world, as well as properly monitor and control all systems on base. These systems must all be maintained preventatively or repaired in the case of failures to ensure safe and efficient operations of the exploration system.

Based on this analysis, a set of ten classes of supply was formulated, representing a high level grouping of the primary objects used in the exploration system.

Table 3.1: Class of Supply (COS) for Exploration Logistics

1.	Propellants and Fuels
2.	Crew Provisions
3.	Crew Operations
4.	Maintenance and Upkeep
5.	Stowage and Restraint
6.	Exploration and Research
7.	Waste Disposal
8.	Habitation and Infrastructure
9.	Transportation and Carriers
10.	Miscellaneous

Each of the ten classes has several sub-classes which further refine the categorization of the supply items (see Table B.6). By assigning each item to a supply class and a sub-class, we allow a flexible multi-level supply class hierarchy which can give us great flexibility in dealing with supply classes at different levels of granularity.

The first step of validation of this classification was carried out by mapping the COS against the current taxonomy used by NATO (Table B.2), the U.S. Military (Table B.3) and the International Space Station (CCART, see Table B.4). A detailed comparison between our functional COS and CCART is shown in Table B.5. The second step of validation was via the HMP expedition itself, which allowed us to validate the functional view of exploration supply classes (Fig. 3.1) and ensured that we did not forget a major class of supply. Physically recording a detailed inventory also forced us to generate a total of 44 sub-classes (see Table B.6) that were complete, non-overlapping and reflective of the physical reality encountered at the research station.

[11] Planetary scientific exploration is typically broken down into different areas such as planetary geology, astrobiology, atmospheric research, volcanism and so forth …

3.2 Inventory Procedures and Results

One of our major goals at the HMP research station was to generate an initial formal inventory of equipment and supplies on base. In future years, a complete base inventory would be taken at both the beginning and the end of the field season, and all shipments to and from camp would be tracked in between, thus creating an accurate time-varying model of the HMP inventory. The data provided in this section, however, represents a single snapshot for the 2005 field season.

In the first season, we expected that seamless accounting would not be possible; instead, our first task was to develop and test procedures for inventorying and tagging items on base. In the process, we hoped to gain a general idea of the scope and difficulties of the inventory effort in order to develop recommendations and improved procedures for later years, and to make our inventory as complete as possible in order to generate a model of base operations (as an analog to a Moon or Mars base). The inventory was also intended to test the newly developed classes of supply (COS) – see previous section - and to populate a relational database for tracking supply items using barcodes and Radio Frequency Identification (RFID) tags (see Section 5).

Prior to arrival at the HMP RS, basic inventory procedures were created. First, the classes of supply were developed (discussed above). Required attributes for each tracked item were discussed and refined, resulting in the partial list below. These attributes were developed for a potential Lunar/Mars base, and then applied to HMP. Attributes developed specifically for HMP might have been slightly different (less emphasis on storage and shipping environments, for example); however, one of our goals was to determine how well HMP operations compared to Lunar/Martian base operation, so Lunar/Mars-applicable item attributes were also used.

- Supply Class
- Item Name, Number of Items
- Item Description
- Priority Level
- Hazard Type, Level
- Perishability Type, Units, Parameter
- Usage Rate, Type
- Origin Type
- Owner
- Storage Environment
- Packaging, Handling
- Mass Units, Type
- Size Units, Type
- Volume
- Cost/Replacement Value
- Percent Full
- Location
- Parent Item (Case)
- Barcode or Electronic Product Code (EPC) Number

An Excel-based inventory file was created to track these attributes. A template provided a basic structure, and separate inventory sheets were created for each location on base (see Fig. 2.3 for a HMP base layout) or major category of equipment (see Table B.6). This distinction was for convenience only, and did not affect the final database. Figure 3.2 shows a screenshot of a portion of the food inventory file. For each item an actual mass was recorded, so that we could estimate the total mass of the HMP inventory[12]. For some items we recorded the volume and extrapolated mass based on a density estimate. Perishability was only recorded if an actual expiration date was visible on the supply item.

ItemID	SupplyClassID*	Name	Description	PerishabilityType	MassUnitsTypeID	Mass	SizeUnitsTypeID	Volume	NumOfItems	Location
1	202-[	Coffee, can		0-[Not Perishable]	1-[kg]	1.10			9	10-[Research Tent 1]
2	202-[	Coffee, bag	Arabica	0-[Not Perishable]	3-[lbs]	5.00			2	10-[Research Tent 1]
3	202-[	Instant coffee, jar	Folgers	0-[Not Perishable]	3-[lbs]	0.75			2	10-[Research Tent 1]
4	202-[	Whole bean coffee, bag		0-[Not Perishable]	3-[lbs]	5.00			1	10-[Research Tent 1]
5	202-[	Basket coffee filters, bag		0-[Not Perishable]			14-[Qty]	200.00	3	10-[Research Tent 1]
6	202-[	Basket coffee filters, bag		0-[Not Perishable]			14-[Qty]	700.00	1	10-[Research Tent 1]
7	202-[	Cone coffee filters, bag		0-[Not Perishable]			14-[Qty]	400.00	1	10-[Research Tent 1]
8	202-[	Instant coffee, jar	Nescafe	0-[Not Perishable]	1-[kg]	0.20			9	10-[Research Tent 1]
9	202-[	Iced tea mix, can	Nestea	0-[Not Perishable]	1-[kg]	2.70			6	7-[Outside, Camp]
10	202-[	Yeast, packet	Instant Qui	0-[Not Perishable]	1-[kg]	0.01			17	7-[Outside, Camp]
11	202-[	Yeast, can	Instant	0-[Not Perishable]	1-[kg]	0.11			2	7-[Outside, Camp]
12	202-[	Corn starch, box		0-[Not Perishable]	3-[lbs]	1.00			1	7-[Outside, Camp]
13	202-[	Pancake syrup, jug	Maple	0-[Not Perishable]			10-[L]	4.00	2	7-[Outside, Camp]
14	202-[	Corn syrup, bottle		0-[Not Perishable]			10-[L]	0.50	2	7-[Outside, Camp]
15	202-[	Honey, bottle		0-[Not Perishable]	3-[lbs]	5.00			2	7-[Outside, Camp]

Figure 3.2: **Excel inventory file (excerpt). This worksheet catalogs only food items.**

This template was modified and refined as the on-base inventory proceeded. One of the major modifications was the addition of the 'Parent Item' or 'Case' attribute. Based on conversations with HMP participants, it became clear that tracking a location at the previously envisioned level of 'tents' or 'modules' would not be useful. People generally knew what area or tent a particular item resided in; what they needed from an inventory was exactly where in that tent the item was located. For example, food left on base over the winter was stored in large white coolers labeled with numbers. Some coolers were stacked behind the mess tent, and others were used as seats in various tents. Jack (the cook) continually wanted to know which cooler contained certain kinds of food. Thus, we created a field to track parent items. In this manner, a coffee can, for example, could be located in cooler 17, which resided in the research tent. One of our major recommendations to NASA (see Section 7.4) is derived from this experience.

Based on field observations, we also added a "*Percent Full*" attribute. It was especially important to track the '% full' status of fuel drums on base; many of these were in fact empty or nearly empty. On a Moon or Mars base fuel might be tracked by volume (e.g. liters) or mass (e.g. kg), but in the HMP context, it made more sense to track whole drums. In an automated asset tracking

[12] Mass, to first order, is the primary driver of space logistics (transportation) requirements.

environment the %-fill level of various supplies could be reported in an automated, real-time fashion, but this is currently not possible at the HMP RS.

The inventory procedures were also refined while at HMP through trial and error. The inventory was required to accomplish two major objectives: create a line-item in the appropriate inventory sheet for every type of supply item (e.g. instant coffee jar, 0.75 lbs, see Figure 3.2), and tag each inventoried item with a barcode and an RFID tag. The inventory and tagging procedure that was developed is given below.

1. Print a sheet of numbered bar code labels with appropriate class of supply identifiers.
2. Attach a blank RFID tag to the back of the bar code label, and program the RFID tag with the same bar code number. Re-attach the two tags to a nonstick backing paper, and take this sheet of combined tags into the field.
3. Inventory a location (e.g. Mess tent) or a category of supplies (e.g. food). These inventory divisions may be chosen for convenience, as long as they are consistent and items are not double-counted.
4. Record each item's attributes in the inventory sheet, and concurrently tag items with the combined tags, recording the number for each in the Excel inventory sheet.
    a. Tag metal items and bottles of liquid with a separator (e.g. paper, cardboard) under the tags, in order to allow the antennas to read the RFID tags[13].
5. Import the Excel inventory sheet into the SQL relational database.

We also developed conventions for cataloging, naming, and describing various types of items. Examples from our field notes are:

- ***Inventory Sheets:*** For multiple copies of the same item that have identical attributes (name, location, percent full, etc.), enter them as a single line-item in the spreadsheet and record the number of items. However, if there are two of the same item with different attributes (e.g. two cans of coffee, one half-full, another entirely full), create two separate line items, but ensure that they have the same name.

- ***Food:*** The "name" field should describe the item generically, but include brands when in common use. Otherwise, brands go in the description field. This will enable categorizing foods and other items by generic categories such as "cookies", not just "Oreos". Consistently using these keywords is critical for subsequent queries of the SQL database.

Thus, after the first week on base, the team developed and finalized a straightforward inventory procedure and supporting spreadsheet/database. Minor changes and refinements continued throughout the field season. Following the process described above, the following locations (see Fig. 2.3) were inventoried by the team:

- Bathroom Tents
- MIT Tent
- Office Tent (inc. medical supplies)

[13] Metal objects and those containing liquids proved to be difficult to read by the RFID system. Various measures must be taken to ensure that such items can be read in the future. More details are given in Section 5.

- Research Tent
- Core Module
- Mess Tent (incl. food)
- Arthur C. Clarke Greenhouse
- Systems Tent (Communications, Computing)
- MARS-1 Humvee Rover
- Outdoor research station equipment

In each location, all items that were at the HMP research station for base support or science purposes were inventoried. We did not systematically inventory personal items that were being kept in any of the locations listed above (such as CD players, water bottles, clothing, etc) with the exception of personal items of the MIT team. We also did not inventory the contents of any of the personal sleeping tents (see Fig. 1.2). Inventory and tracking of personal items was deemed to be the responsibility of each individual[14] and we also wanted to avoid being overly intrusive. As a general rule of thumb, HMP assumes that an individual and their personal gear amount to a total weight of about 300 lbs. One of the difficulties of maintaining an accurate inventory at the HMP RS is that research teams are constantly arriving and departing throughout the field season along with some of their research-related and personal equipment.

Over 2300 items were inventoried by our team during the 2005 field season. These items were cataloged in a multi-sheet Excel file (see Figure 3.2 for an excerpt from a single sheet). In this spreadsheet, each location (Mess tent, MIT tent, etc.) has its own tab with the complete list of attributes across the columns. Within each tab items are sorted by supply sub-class (see Table B.6). A summary mass breakdown of the 2300 items inventoried by sub-class of supply and location can be found in Appendix C. We also analyzed the inventory by ownership.

From the inventory data we collected, some interesting results can be observed.

The first analysis we performed on this data was to divide the 2300 items by class of supply and then by sub-class. The results of this breakdown can be seen in Figure 3.3. The results by sub-class show that nearly one fourth of the entire inventory at the research station was due to food and related equipment (COS 2.2, 23%). The second quarter was comprised of communications equipment (COS 3.5, 15%) and science instruments (COS 6.1, 11%), followed by health related equipment (COS 3.3, 9%). This last supply class may be surprising, but HMP maintains a high level of medical capability, both through personnel (certified flight surgeons) as well as a variety of expeditionary medical supplies and sophisticated equipment (e.g. CSA telemedicine kit).

The second analysis was to analyze the mass breakdown of the total of 20,717 kg (~ 46,000 lbs) that were recorded at HMP. Figure 3.4 shows the mass breakdown of the HMP 2005 inventory by the 10 functional classes-of-supply (COS). In the figure, the COS start at the 12 o'clock position, and are then enumerated going clockwise. The raw data used to generate the inventory mass breakdown is contained in the SQL database but is too voluminous to reproduce here. Nonetheless, a summary of the HMP mass breakdown by sub-class of supply and location on base is provided in Appendix C, Table C.1.

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[14] For Moon and Mars exploration, however, personal items must be managed together will all other classes of supply as they will have a non-negligible mass and stowage volume impact.

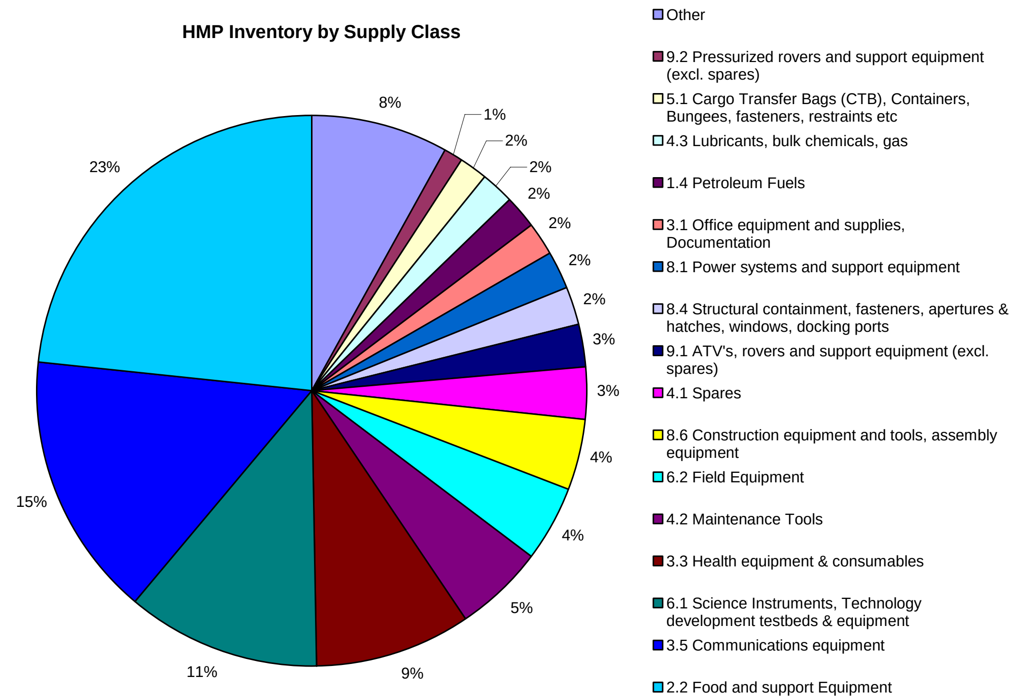

Figure 3.3: HMP Inventory by Supply Sub-Class (read counterclockwise)

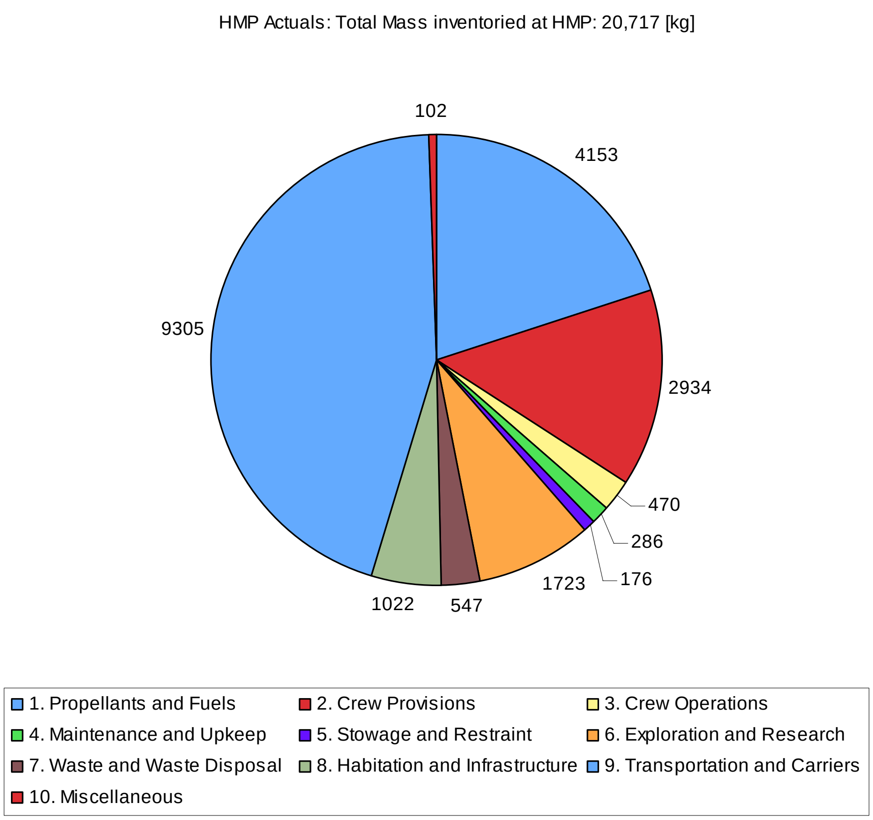

Figure 3.4: HMP mass breakdown by class of supply in units of kg (read clockwise)

We note that transportation items (COS 9, 46%) dominate the total mass of supply items at HMP. This is primarily due to the presence of 13 All-Terrain Vehicles (ATVs), which each weigh between 227-325 kg and the Humvee itself with a curb weight of at least 4700 kg. This is followed by the various fuels and propellants that are stored at the HMP research station (COS 1, 20%), crew provisions (COS 2, 14%) and exploration and research equipment (COS 6, 8%). Figure 3.5 shows a breakdown of the different fuels and propellants by type[15]. Diesel is used to run the electricity generator(s) and some of the newer heaters, gasoline is used for the ATV's, there is an emergency supply of aviation gas for the Twin Otters, and propane is used for heaters and cooking. Figure 3.5 shows the fuel distribution at HMP by type of fuel. This is useful because, with no formal fuel inventory management already in place, it is difficult to determine when to re-order each type of fuel.

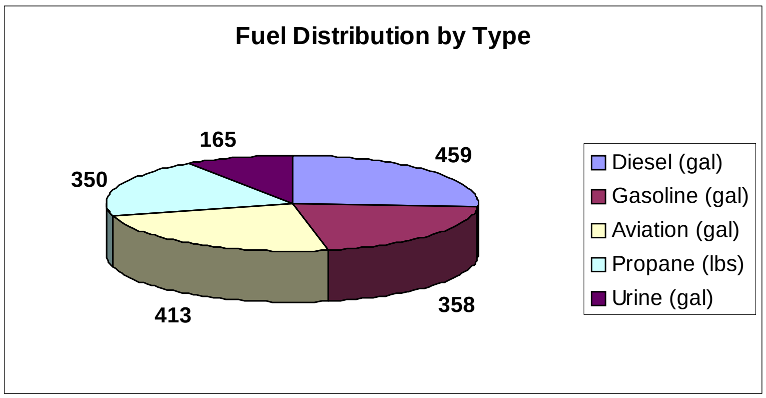

Figure 3.5: Fuel Distribution at HMP (2005) by type [gal] (beginning of 2005 season)

Another interesting application for the collected inventory data is real-time inventory management and tracking. We did not fully implement such a system this year, but we experimented with informal, ad-hoc inventory management to determine its usefulness for the HMP RS (Section 5). The most 'popular' aspect was the application to food items. Another useful application is illustrated in the next few paragraphs: we used our inventory to analyze the distribution of fuel around the base, by type and location. In fact, in the course of our inventory we cataloged twelve empty propane canisters (on which HMP was paying rent); this alerted camp managers to their presence and they were promptly shipped off base (see flight #7, Appendix F), saving HMP money.

One of the challenging aspects of taking inventory at a research station like HMP is that similar items might be distributed at different locations on base. This also contributes to a difficulty in managing the levels of each fuel type at HMP. Fig. 3.6, for example, shows the distribution of fuel and propellants from Fig, 3.5, broken down by location on base.

[15] Note that "urine" is listed here, even though it belongs in supply class 7.1 (waste). The reason is that at HMP urine is collected in empty fuel drums for ecological reasons and shipped from HMP to Resolute for proper disposal (reverse logistics).

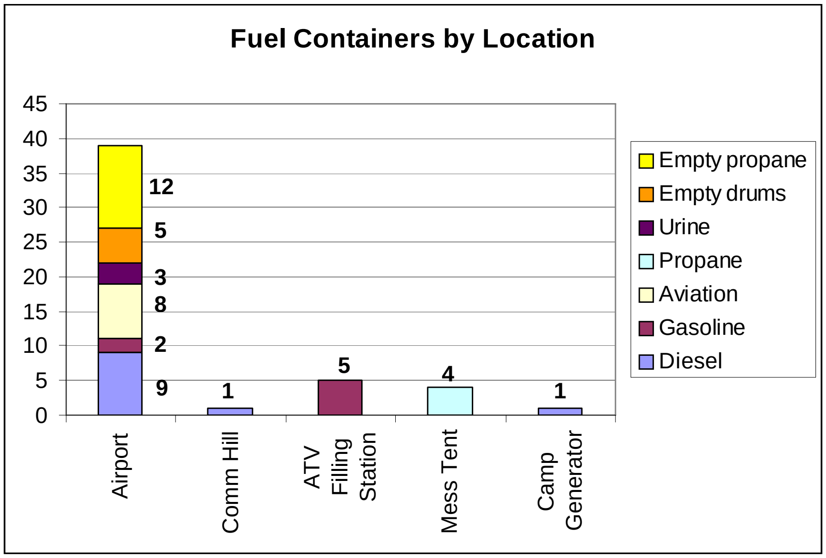

Figure 3.6: Fuel Containers (55 gallon drums[16]) by location at the HMP RS

The sketch in Figure 3.7 shows the local topography around the HMP research station and correlates with the locations shown in Fig. 3.6 and the aerial view in Fig. 1.2. This topography illustrates the difficulty of inventory management over such widespread locations in a relatively difficult environment. We expected these challenges to also exist on a research station at the Moon and Mars.

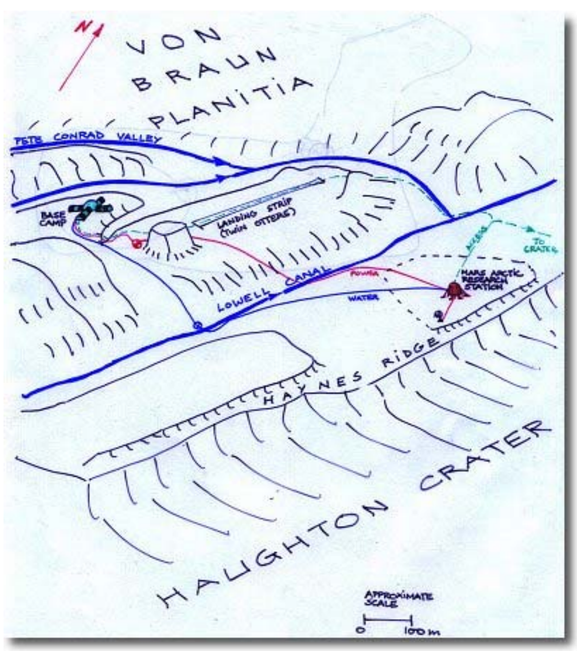

Figure 3.7: Perspective sketch of the HMP Base Camp area (left). Also indicated is the Mars Society's MARS habitat (right). Power and water lines are indicated in red and blue, respectively. Access trails are indicated in green. Source: [5, sketch is pre-2005]

[16] All fuels are stored in standard 55 gallon drums, with the exception of propane bottles.

This section has shown a couple of examples of the varied uses of HMP inventory data, both in terms of understanding the distribution and levels of supplies by supply class across the base, as well as in real-time inventory management applications. The next step is to compare the actual data for HMP to pre-expedition estimations for HMP and to models for a lunar base, in order to verify these models and to understand the degree of analogy between HMP and planetary exploration research stations on the Moon (and eventually on Mars).

3.3 Comparison between HMP and a Lunar Base

Based on the actual inventory data obtained from the field season, we attempted to quantify the extent of analogy in various classes of supplies. Figure 3.8 shows a comparison by class of supply between HMP actual inventory data ("HMP Actuals" – red bars), pre-HMP expedition estimates ("HMP Est." – green bars) as well as two parametric lunar base logistics models derived from the recent Draper/MIT Concept Evaluation and Refinement project [7]. We modeled both a 180-day long lunar mission model with habitat ("Lunar Long" – blue bars) and a short 10-day Apollo-style mission model without habitat ("Lunar Short" – yellow bars). Predictions for crew provisions are for 684 crew-days. The underlying data is in Appendix D.

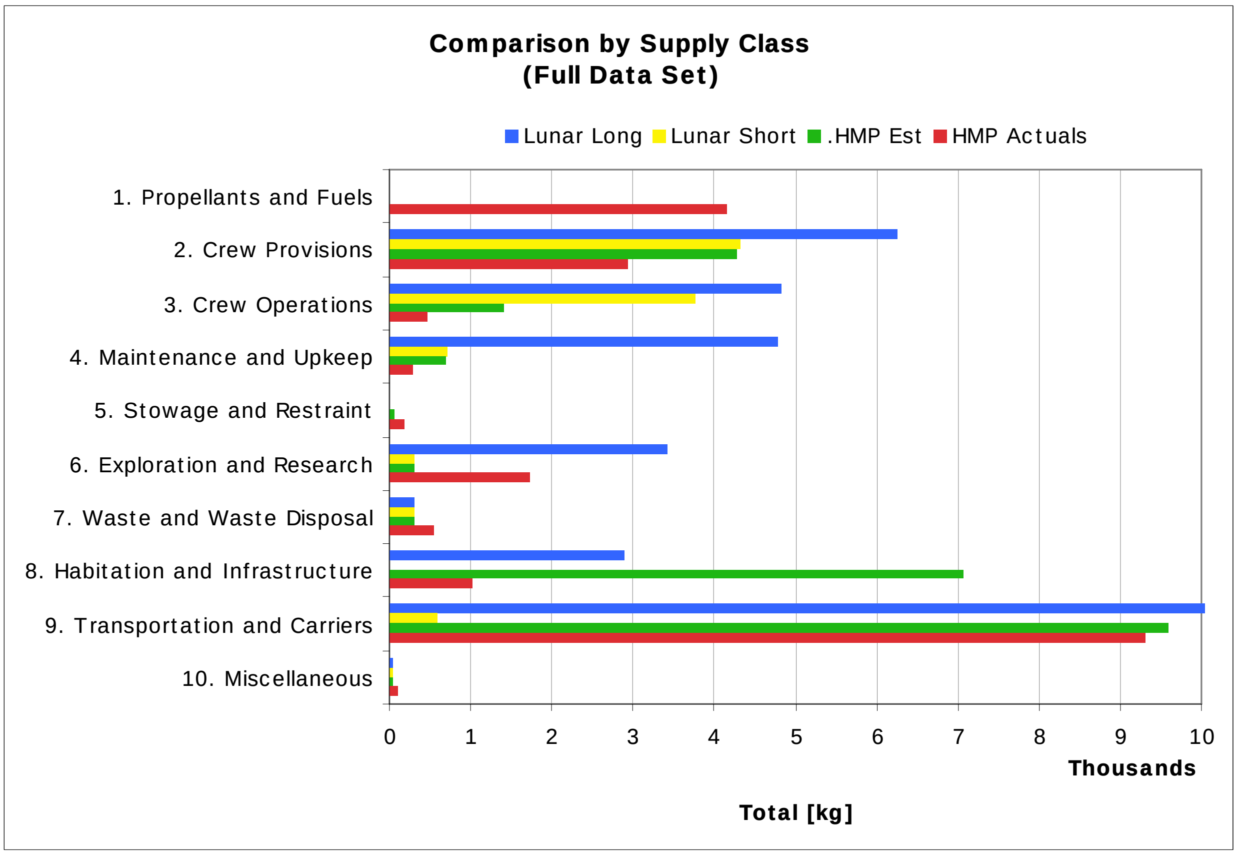

Figure 3.8: Mass comparison between HMP Actual data and estimates based on a parametric exploration base demand model. The models (HMP Estimate, Lunar Long, Lunar Short) all assume 19 crew members for 36 days, to arrive at a total of 684 crew days on the surface, which is what occurred during the 2005 HMP field season.

When examining Figure 3.8 several differences are apparent; the most obvious such difference is **COS 1**, the Propellants and Fuels. Our HMP estimate for propellants and fuels was zero based upon the fact that these items were accounted for differently in our previous CE&R work [7] and are *mainly associated directly with in-space transportation vehicles* (e.g. the CEV, LSAM, or a pre-positioned habitat). Additional work will be required to distinguish between fuels and propellants used for transportation *to and from* the base, and fuels used while *on* base, including for surface mobility. A large difference can also be noted in the maintenance and upkeep (COS 4), exploration and research (COS 6) and habitation and infrastructure (COS 8) classes. These differences will be explained below. Note that the input parameters into the HMP estimated demand model were a hypothetical mission duration of 36 days (same as the original HMP 2005 schedule) and a crew size of 19 to reproduce a comparable number of crew days on the surface (684) as what actually occurred at HMP, see Section 4.2.

3.3.1 Modeling Assumptions

The HMP estimate (green bars) is based on models for human lunar exploration missions. Surface 'demand' models were developed for the NASA CE&R study at MIT [7], which estimated the required supplies (by mass) for surface missions on the Moon and Mars. Separate models incorporate assumptions appropriate to 'short' lunar missions (approximately 10 days on the surface, yellow bars), 'long' lunar missions (approximately 180 days, blue bars), and Mars missions (600 days on the surface, not shown). The basic assumptions and numbers for the long (blue) and short lunar models (yellow) are given in Table D.2, along with the appropriate references from HSMAD [9], where appropriate. For the HMP work, the CE&R lunar models were adapted to generate estimates of required equipment within the ten supply classes. The equipment and mass estimates are based in large part on the relationships given in Larson and Pranke for Human Spaceflight Mission Analysis and Design (HSMAD) [9], which were developed based on experience with past manned spaceflight programs. Some of the comparisons below are based on the 'short' and 'long' lunar surface demand models.

For the purposes of comparing the HMP actual inventory data to a 'best estimate', the lunar demand models were slightly customized for HMP. Based on apriori information about the mission and capabilities of the HMP research base, a model was developed utilizing the same basic relationships as the lunar demand models, but incorporating other HMP-specific factors. The comparison between the HMP estimate and the HMP actual numbers is shown in Table D.3. For the most part, the modeling assumptions for each supply sub-class are the same as those in the lunar short and long mission models. Wherever the lunar short and long duration models differ, a choice was made between them based on the supply sub-class. For personal items and certain research-related equipment, the short mission model is more appropriate, because each person at HMP is generally on a short-style mission (i.e. in residence for ~12 days rather than ~180 days). However, for infrastructure and some permanent science equipment, HMP bears greater similarity to the long missions (which build up permanent infrastructure), rather than the short sortie-style missions.

In some cases neither the short nor long lunar missions was an appropriate model. Estimates for specialized HMP equipment (such as ATV's or generators) were added to the model in that case.

Other HMP-specific estimates have also been included: the number of EVA suits (to be tested at HMP), tents (assuming a total mass of 1000 kg for each of the seven tents), and vehicles, for example. Thus, the HMP estimate is intended to represent the best pre-expedition surface demand model that could be created for HMP *given the current level of knowledge and modeling ability* for human planetary bases. The estimate is then compared to the results of the actual HMP inventory in order to assess the accuracy of our current planetary base modeling methods.

3.3.2 Comparisons by Sub-class

In an effort to compare HMP to a lunar base, estimates from the MIT/Draper CE&R Study [7] for a lunar long mission and a lunar short mission were used to estimate the required mass of each exploration sub-class of supply. Recall that a lunar long mission is understood to be a 180 day surface mission and a lunar short mission is a 10 day "Apollo style" sortie mission. These three estimates were then plotted against the actual HMP inventory data collected by the MIT team during the 2005 field season. The degree of HMP analogy by sub-class is given below.

COS 2: Crew Provisions

From Figure 3.8, it appears that the HMP estimate for class of supply 2, crew provisions, is about 1300 kg larger than the HMP actual inventory. When COS 2 is broken down into its sub-classes (Figure 3.9) the sources of this difference become apparent.

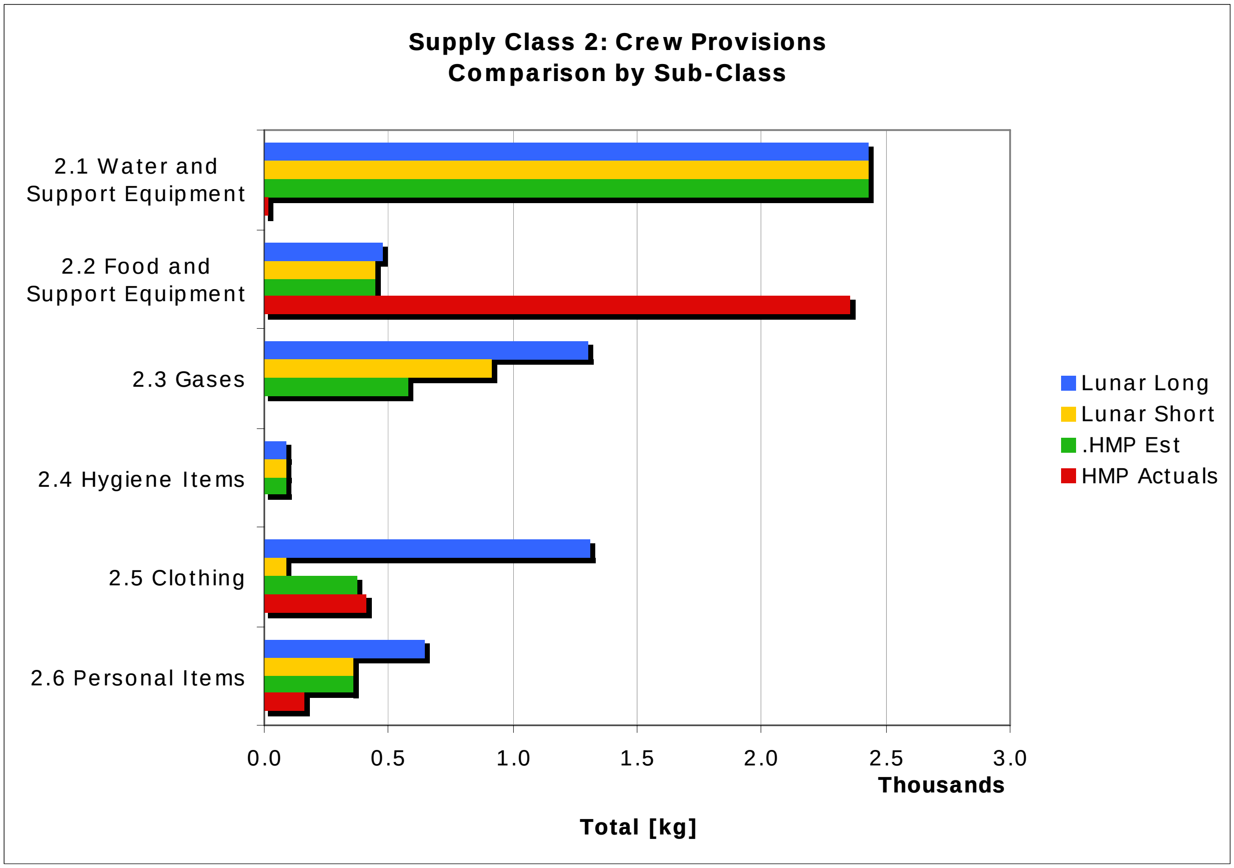

Figure 3.9: COS 2 Comparisons by Sub-class

We see from *COS 2.1* that almost no water is imported to HMP in actuality because of local resource usage, whereas the models predict that 2428 kg of water would have to be shipped in otherwise to support the field season. This assumes a net water consumption of 3.55 liters[17] per person per day [9]. We suspect that actual numbers will fluctuate greatly based on weather, activity levels of the crew, conservation policies at camp as well as %-ECLSS closure (if applicable). *It would be interesting to monitor the actual usage of water at HMP by installing a simple flow meter in the main water feed line* (see recommendations in Section 7).

One the flipside, the comparison for *COS 2.2*, food and support equipment, shows the HMP actual figures outweighing the HMP and lunar estimates by nearly 1900 kg. This is certainly due to the large oversupply of food at HMP. HMP has stockpiled several seasons' worth of food, as well as a wide variety of kitchen equipment. HMP at one point received a C-130 airdrop, and took advantage of the opportunity by shipping as much canned food as possible[18]. Thus, the HMP food actuals are a significant overestimate of actual integrated HMP food consumption rates. Another contributor to the difference is that spaceflight estimates are based on the use of dehydrated food (0.64 kg per person per day), which is much lighter.

COS 2.3 comprises gases that must be provided for crew consumption (oxygen, nitrogen, buffer gas). Typically, these must be imported with an oxygen consumption rate of 0.84 kg per person and day as a basic estimate. Obviously, gases are used directly from the environment at HMP and the pre-HMP estimate should have already reflected this. Personal hygiene items (*COS 2.4*) were certainly present at HMP but were not inventoried, since they were kept in the individual sleeping tents.

The clothing (*COS 2.5*) long lunar mission estimates allow for 69 kg per crew, short lunar missions allow for 4.6 kg per crew and the HMP estimate allowed for the same 4.6 kg (indoor) clothing per crew, plus an allowance of 15 kg per crew for outdoor clothing. Outdoor clothing for HMP was estimated here (not under COS 3.2 EVA equipment), based on the luggage allowance at First Air. A total of 408 kg of various clothing, mainly from the MIT team was nevertheless inventoried. The main reason why long lunar missions have a much larger allowance for clothing is that a washing machine is generally not assumed to exist due to the significant water consumption that would be required for its operation. This is the same situation as on ISS, where dirty clothing is treated as waste, rather than washed[19]. Personal Items (COS 2.6) are items such as music players, personal cameras, books, etc… and again a larger allowance (25 kg per person vs. 10 kg per person) is made for the longer missions. Sleep provisions are estimated at 9 kg per person. The HMP actual numbers contain some personal items, but as was mentioned above, a complete inventory of all personal items of all 56 HMP participants was not taken for privacy reasons. Had we done so, the actual HMP numbers would likely be much closer to the estimates.

[17] 1 liter of water = 1 kg

[18] Much of this stockpile is in the form of 1 gallon cans of various foods, stored outside near the greenhouse, which are over 5 years old and past their expiration at this point. This, along with the significant freeze-thaw cycles undergone by the cans due to the Arctic seasons, reluctance by the camp cook(s) to use these unknown reserves and health concerns expressed by the flight surgeons, probably renders this HMP food cache unfit for human consumption.

[19] Space Station Freedom had a washing machine in one of its early design iterations; this was eliminated for ISS.

For crew provisions (COS 2) in general, we conclude that local availability of water and oxygen at HMP are the main contributors that make HMP non-analogous to the lunar demand models. We could change the lunar models to include the use of ISRU, but this would also require adding an ISRU plant (COS 8.5) and associated power system (COS 8.1), which would be needed on the Moon and Mars, but not at HMP. The food comparison shows that HMP is also not analogous to space exploration, mainly because it does not use dehydrated foods and has created a large cache of (heavy) canned food. The other items (hygiene, clothing, and personal) are quite analogous.

COS 3: Crew Operations

In Figure 3.8 the estimate for HMP Crew Operations Equipment (COS 3) exceeded the actual recorded inventory at HMP (470 kg) by about 1 metric ton. The short lunar (10 day) and long lunar (180 day) missions predict a need for 4 tons and 5 tons of crew operations equipment, respectively. From Fig. 3.10 we see that this difference is primarily driven by *COS 3.2*, EVA Equipment and Consumables. The HMP estimate takes into account that pressurized EVA suits are not needed on Earth as they are on the Moon (in fact EVA requirements are a major logistics driver for the Moon and Mars, especially in terms of stowage volume), but that some EVA suits will be tested at HMP. It was assumed that 5 EVA suits (each weighing 119 kg) and associated consumables and work aids would be required at HMP, whereas the single Hamilton Sundstrand test suit brought to HMP in 2005 (see Appendix I) turned out to be much lighter.

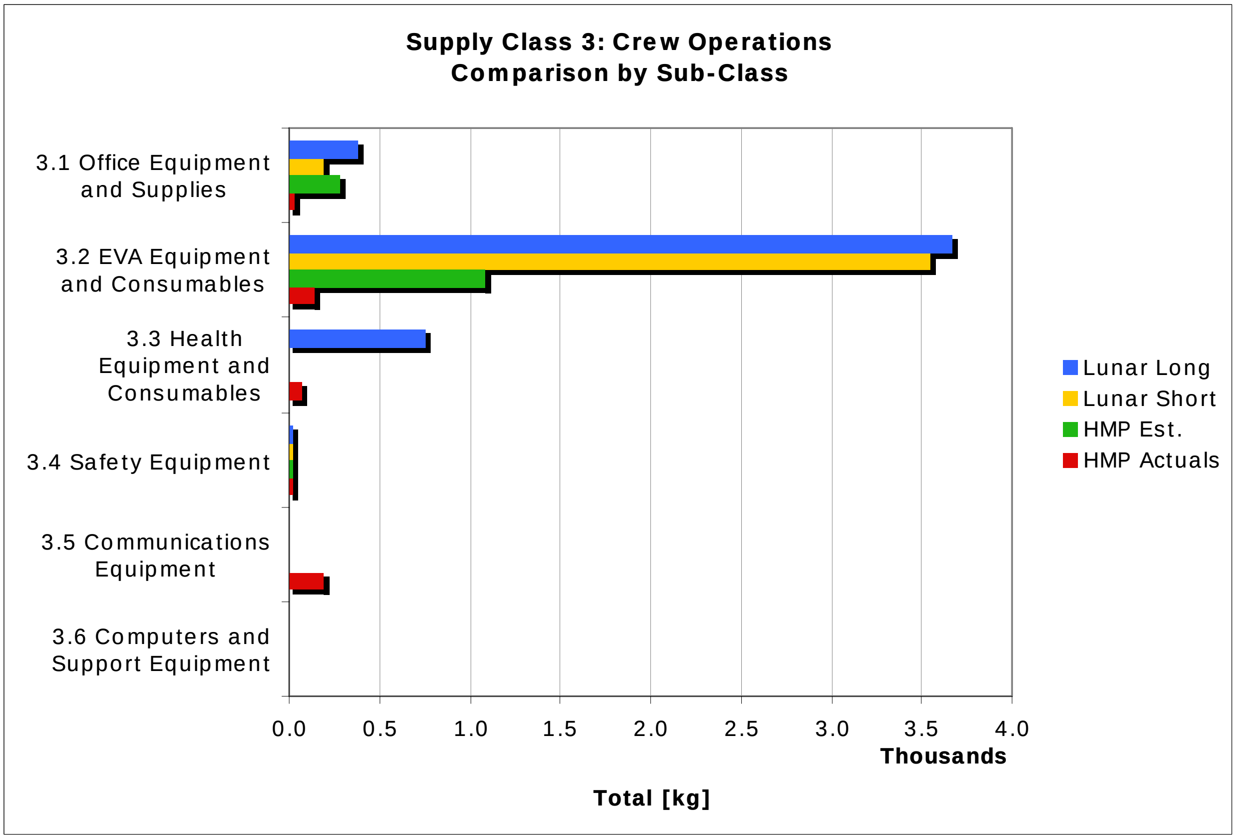

Figure 3.10: COS 3 Comparisons by Sub-Class

Actual and predicted office equipment (*COS 3.1*) was below 500 kg.

Health (*COS 3.3*) and Safety (*COS 3.4*) equipment is essential, but it is not very heavy or bulky. While the emphasis at HMP is on preventing individuals from getting lost in the field, or attacked by polar bears, most of the safety equipment associated with Moon and Mars missions [9, HSMAD, pp.472] centers on fire prevention and suppression. For long lunar missions the model assumes that a Medical/Surgical/Dental Suite (500 kg) and associated Medical/Surgical/Dental/Consumables (250 kg) will be carried along. Even though some medical supplies exist at HMP, they are quite basic in nature. The sophisticated medical equipment mentioned earlier (e.g. CSA telemedicine kit) was likely book-kept under scientific equipment (*COS 6.1*) as it had clear research objectives associated with it, but its classification might as well have been under COS 3.3. Also, as will be seen later, HMP does have a medical evacuation plan in case of emergencies, which alleviates the pressure on this class of supply.

The lack of mass data around communications equipment (*COS 3.5*) and computers and support equipment (*COS 3.6*) was somewhat puzzling at first and brings up a few interesting points.

Clearly, HMP has a suite of sophisticated communications gear (C-band satellite transceiver, parabolic antenna, on-site wireless network,…) but it is unclear whether this equipment was entirely classified under COS 3.5, or under COS 6.1, since some research objectives are also associated with the communications work done by Dr. Braham and his team. Furthermore, we found that much of the communications and computer equipment present at HMP is mobile, whereas in lunar and Martian missions, much of this type of equipment would be fully integrated into the vehicles and habitats, or into the EVA suits, which is the likely reason why nothing is predicted in those sub-classes for the lunar missions. We only accounted for this type of equipment under *COS 4.1* (spares), rather than counting communications and computers as separate supply items.

This supply class clearly shows that the relationship between items already integrated in various vehicles and truly “separate” supply items must be better understood in the future. Also, further research is needed for those items that might be ambiguously classified, depending on whether they provide a “household function” or whether they are in fact destined for a set of technology/science experiments.

COS 4: Maintenance and Upkeep

From Figure 3.8 it appears that *COS 4*, maintenance and upkeep, was slightly overestimated by the parametric HMP base exploration logistics model by ~400 kg. The mass breakdown by sub-class (Figure 3.11) shows the differences.

From Figure 3.11, we observe that the pre-HMP estimate for *COS 4.1*, spares and repair parts, turned out to be double what the actual recorded masses were[20]. There are two main reasons for this difference. The first is that a lot of maintenance at the HMP RS depends on scavenging parts from in-use spares. For example, if one of the ATV breaks, spare parts may be taken from

[20] The spares estimates for the lunar models were taken from a 1999 NASA DRM study, Table 3-13

one of the other ATVs around camp until a new part can be ordered.[21] This leads into the second reason for the difference between the estimates and actuals; although HMP is a remote base, much of the actual maintenance work seems to be based on an "order as needed" strategy. With Twin Otter flights coming in approximately every 3 days (see Appendix F) and First Air flights into Resolute on a twice-weekly basis, spare parts for many systems could be ordered from a major Canadian or U.S. city and arrive at the HMP RS within a week. The MIT team was able to observe this process early in the field season when it was discovered that a critical part of the communications system was damaged due to moisture. Without this part the satellite link and internet connection would not function. After on-site repair was deemed impossible, a new part was ordered from Ottawa and arrived on base a few days later. Clearly, such a strategy would not be possible for lunar missions and that is why significant amounts of spares would have to be taken along or pre-positioned (see large blue bars in Fig. 3.11).

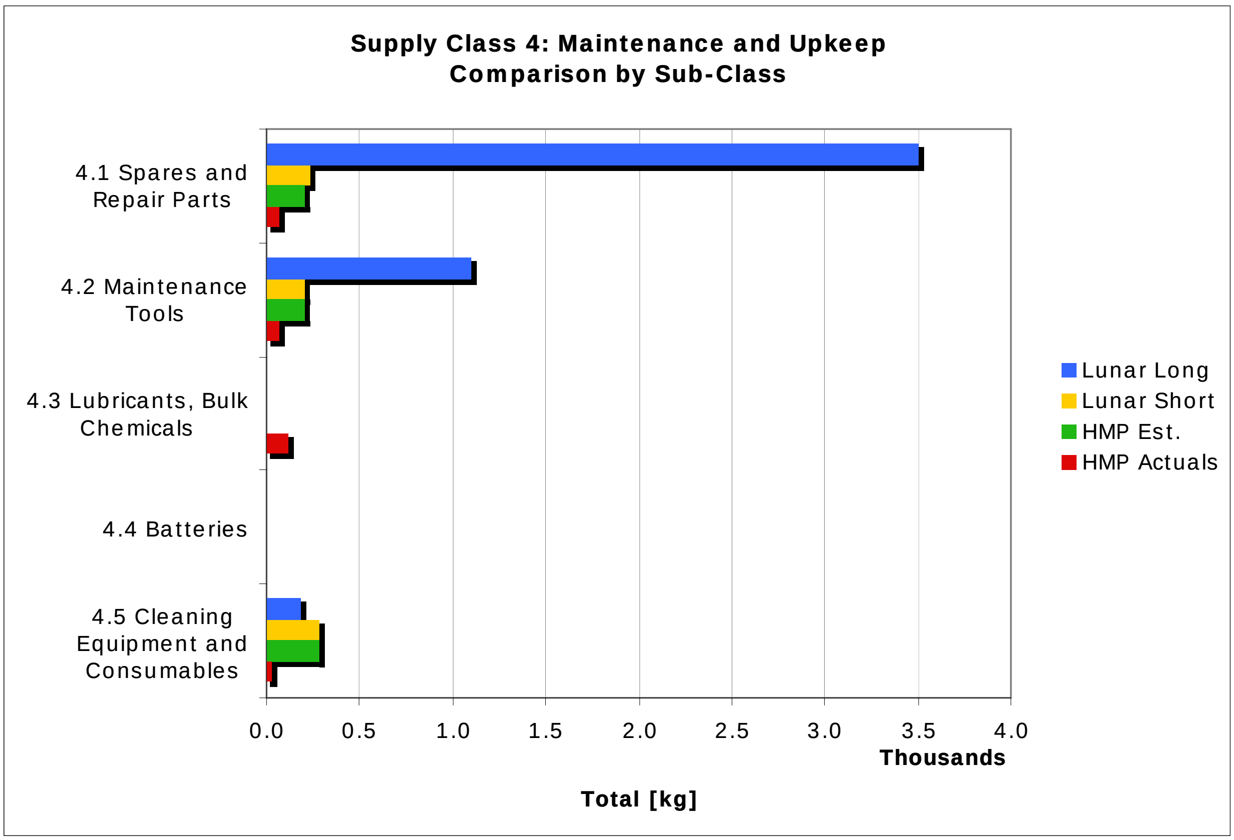

Figure 3.11: COS 4 Comparisons by Sub-class

Maintenance Tools (*COS 4.2*) exist at HMP, but they are generally light-weight and multi-purpose, unlike the heavier and more specialized equipment that is typically used in manned spaceflight operations. Lubricants and chemicals (*COS 4.3*) and cleaning equipment and

[21] This can be an effective strategy for Moon and Mars logistics, provided that (i) reconfigurable and/or common parts are deliberately designed into mission elements and (ii) that these elements are not concurrently in use. In that case scavenged spares can be treated as an additional spares repository. A quantification method for trading off the amount of spares versus functional availability for space exploration, taking into account reconfigurability and commonality, was recently submitted for publication by our team (draft available upon request).

consumables (*COS 4.5*) turned out to be rather insignificant, both in the model and in actuality. However, one of the main lessons learned from Apollo is about the importance of dust mitigation and management, and perhaps this last category has been underestimated. It is also interesting to note that we only recorded a total of 2 kg of batteries at HMP (*COS 4.4*), even though many of them are in use across the research station. We suspect that this is so, because at the time of inventory, batteries were already installed in many pieces of equipment and were not accounted for separately. Even though rechargeable batteries are likely to be used for lunar and Mars missions, it is interesting to note that ISS has an extensive pantry for batteries that needs to be restocked at every crew rotation. Mobile power sources are therefore another, potentially underestimated, sub-class in space logistics.

COS 5: Stowage and Restraint

We did record some amount of containers and stowage equipment (*COS 5.1*) at HMP, mainly large white coolers for food storage, but this category turned out to be rather insignificant in terms of *mass*. However, recent work done on extracting lessons learned from past manned spaceflight projects (Apollo, Skylab, STS, ISS) tells us that the availability and reconfigurability of *stowage volume* is critical. As discussed above, stowage is usually built-in to vehicles and habitats, rather then accounted for as a separate logistics category. Note however, that cargo transfer bags (CTBs)[22], see Fig. 7.1a, are in common use today and might continue to be the standard way in which space logistics cargo is handled in the future. The inventory management equipment (*COS 5.2*) used at HMP consisted of both RFID and barcode readers, see Section 5.

Figure 3.12: COS 5 Comparisons by Sub-class

COS 6: Exploration and Research

This category of supply items is probably one of the most difficult to predict, as it depends very strongly on the particular scientific and technological objectives of an exploration mission. The long lunar model allows for 250 kg of science equipment, associated primarily with a field

[22] One CTBE (cargo transfer bag equivalent) represents a volume of 1.86 cubic feet.

laboratory installed in the habitat. At HMP we classified a large number of items as scientific instruments (and technology testbeds) under *COS 6.1*, that also serve "household functions" (communications, expeditionary medicine) but could also have been classified under COS 3. We believe that the largest contributor to the ~1400 kg of equipment in that class of supply is the Arthur C. Clarke greenhouse[23]. A greenhouse, however, was not present in the baseline Draper/MIT lunar mission model [7], we had developed.

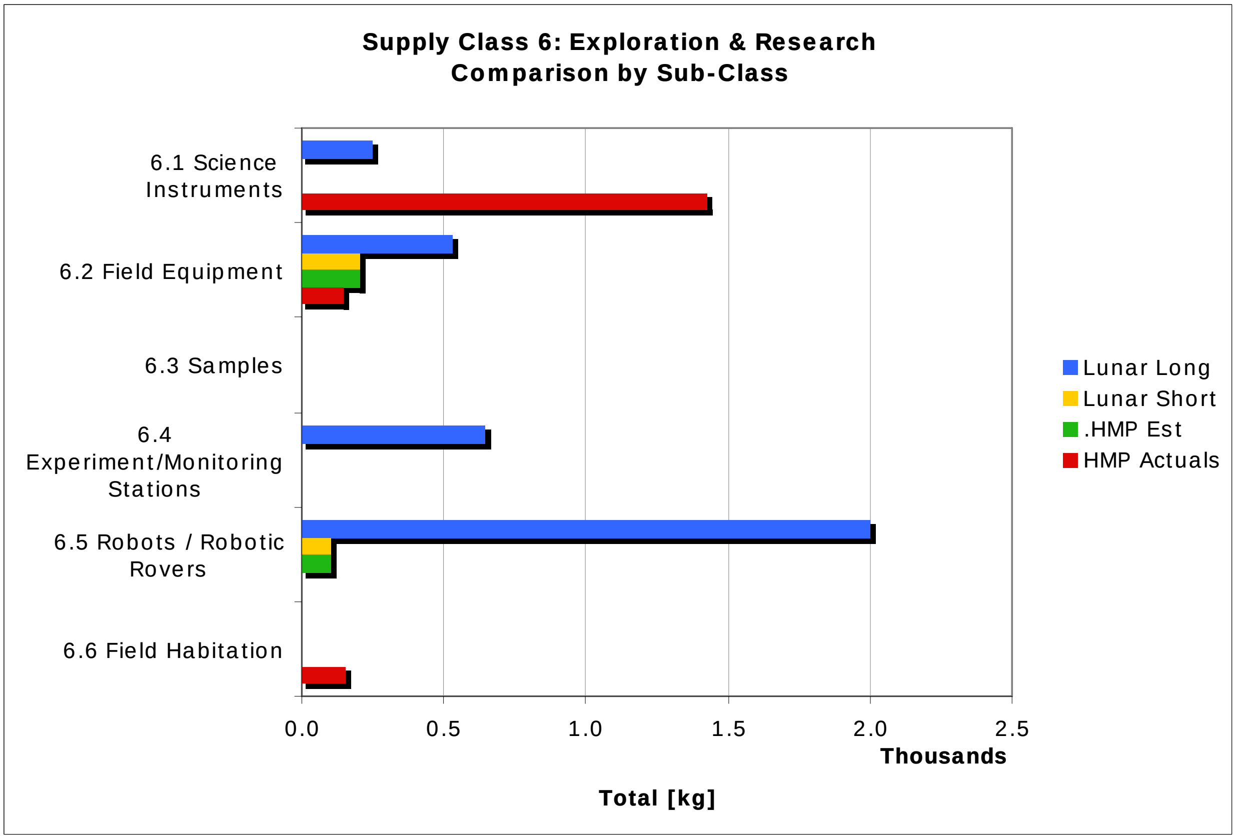

Figure 3.13: COS 6 Comparisons by Sub-class

Field equipment such as cameras, rock hammers, mass spectrometers, portable life science equipment and so forth are captured by *COS 6.2*. Our actual inventory is slightly lower (144 kg), but generally in line with our pre-HMP estimate and short lunar missions (206 kg). We found that the field equipment used at HMP is in some cases an exact analog to what would be used for an equivalent Moon or Mars mission. Appendix I shows some of this field equipment in use. The long lunar mission allows for 300 kg for a drill, and even though an autonomous drill was used at HMP this summer (NASA ARC DAME team), it seems to have been missed by our inventory effort. This illustrates the difficulties we faced with capturing all equipment and supplies of teams (arriving and departing) throughout the field season. More careful tracking, planning and coordination will be required in future years.

[23] Probably the heaviest part of the greenhouse are the large set of 35 batteries, weighting about 70 lbs each, flown in with flight #7 (see Appendix F), representing a total of 2450 lbs. The greenhouse batteries were not accounted for in the HMP inventory.

We did not take inventory of samples (*COS 6.3*) taken from the Haughton Crater, but know that such samples were obtained. In all, however, we suspect that the total mass of rock samples obtained in 2005 was below 200 kg. *COS 6.4*, monitoring stations, e.g. for seismic events, did not correlate with our inventory and we suspect that further refinement will reveal more information in the future. While robots and robotic assistants (*COS 6.5*) were not used at HMP in 2005, they have been present in previous years as exemplified by CMU's Hyperion rover. Future years might see a renewed interest in the testing of robots and rovers at HMP, see Section 7.5. The lunar logistics model has an allowance of 2000 kg for tele-operated or robotic assistants for the long mission (180 days) only. Field habitation (*COS 6.6*) at HMP consists mainly of tents/bivouacs for overnight stays away from base camp.

COS 7: Waste and Waste Management

This category showed an excellent correlation in Fig. 3.8 between HMP and lunar/pre-HMP predictions in terms of mass (303 kg vs. 547 kg). This correspondence at the COS level, however masks some information that can be obtained by going to the sub-class level (Fig. 3.14).

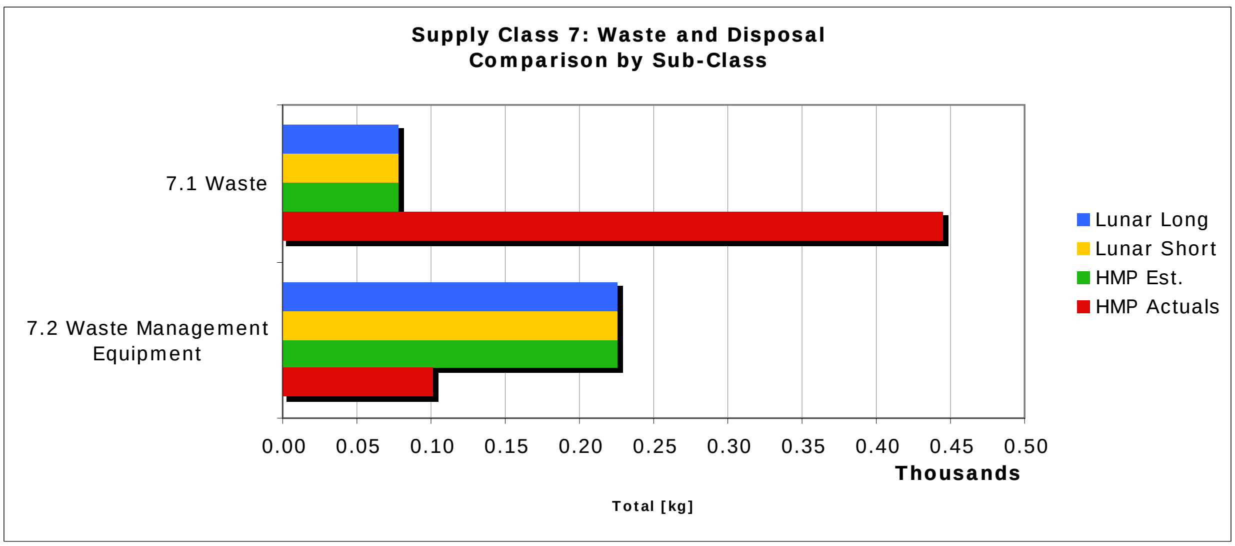

Figure 3.14: COS 7 Comparisons by Sub-class

Human waste (*COS 7.1*) at HMP is handled in two ways. Liquid waste (urine, see also Fig. 3.5) is collected in empty 55-gallon fuel drums and shipped off base for proper disposal at Resolute. The reason is that one wants to avoid depositing organic matter at the HMP site as much as possible, to preserve its pristine ecology and scientific integrity. Thus, the ~450 kg of waste in Fig. 3.14 change dynamically depending on waste production by expedition participants, and reverse logistics shipments.[24] Solid waste (both human and other) is generally burned at a diesel-fired incinerator close to the airstrip.

The total mass for HMP waste management equipment (*COS 7.2*) is somewhat lower than for the lunar case, due to the difference in technological sophistication: the HMP system is quite simple, and depends largely on the use of trash bags (even for human waste). On the other hand, a waste

[24] See flight #17 in Appendix F for an example of such a flight.

collection system for Moon/Mars bases would probably incorporate sophisticated equipment for water reclamation from urine, and attempt to minimize the use of disposable elements such as trash bags.

COS 8: Habitation and Infrastructure

From Figure 3.8, it can be observed that the actual HMP masses for *COS 8*, habitation and infrastructure, are significantly under the estimates. This difference is entirely due to the differences in masses in *COS 8.4*, the structural containment. As noted earlier, we did not (yet) inventory the mass of the erected structures at HMP and they are therefore not included in the actual numbers. The MIT team determined that the core structure was not analogous to that which may be found at a lunar/Mars base (due to the extensive use of wood). The greenhouse structure was excluded for similar reasons and partially because the Draper/MIT CE&R study did not include a greenhouse in their analysis so adding in the mass of the greenhouse would greatly skew our data. We plan on including a more detailed record of actual HMP infrastructure masses in future years. We expect that the HMP actuals will be heavier than the estimates largely because of the heavy materials used to construct the work tents (MIT Tent, Office Tent, Comm/Systems Tent, etc,). These tents are constructed out of three materials: wood (density ~500 kg/m^3), aluminum rods (density ~2700 kg/m^3) and heavy canvas (density ~1 kg/m^2). It is expected that construction materials for lunar/Martian base will be of lower density, but higher stiffness.

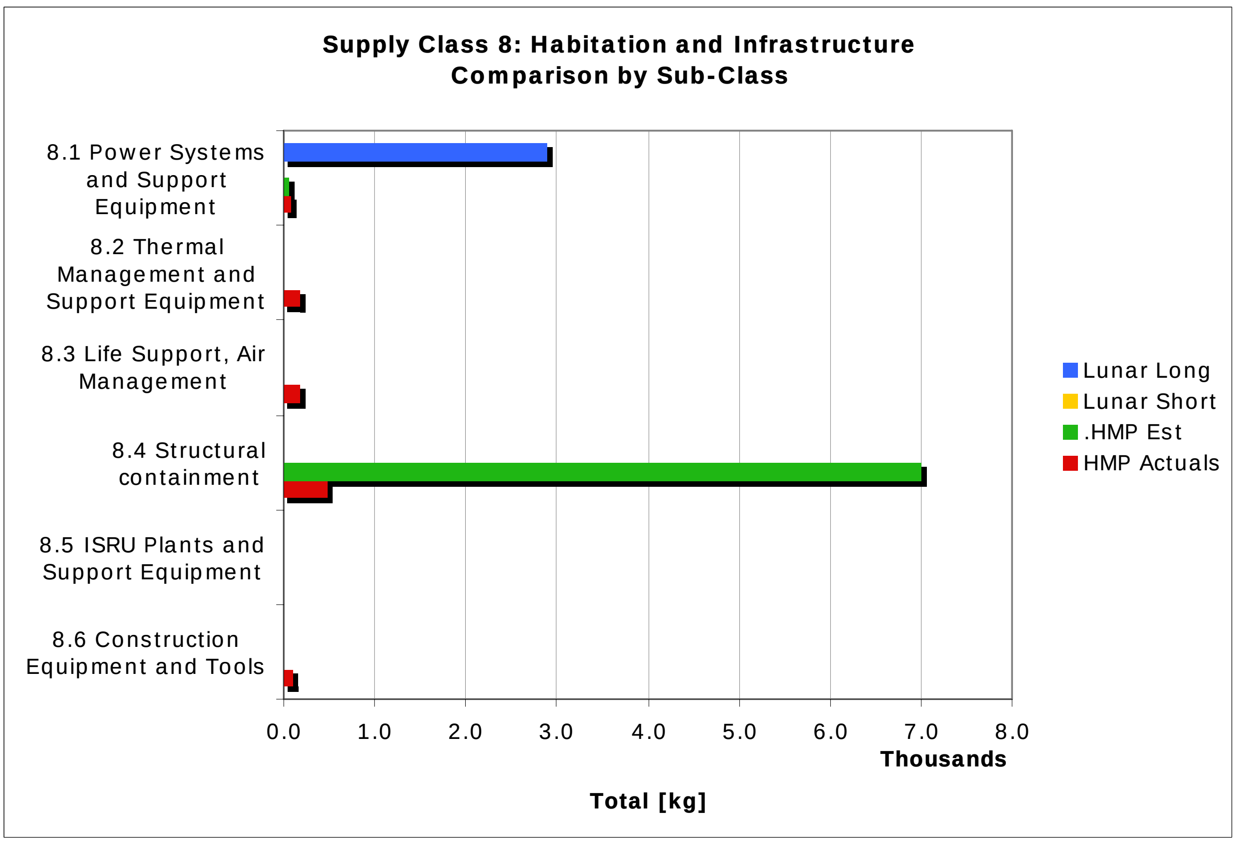

Figure 3.15: COS 8 Comparisons by Sub-class

The long duration Draper/CER [7] lunar mission has an allowance of 2900 kg for a photovoltaic power plant, whereas the recently released ESAS study [8] foresees an initial nuclear power plant on the order of 25kWe at 8420 kg [8, Chapter 4]. Power at HMP (*COS 8.1*), on the other hand, is generated via diesel generators, that are light-weight, but require a substantial amount of fuel (see large COS 1) to operate. The only exception at HMP is the Arthur C. Clarke Greenhouse which operates on a hybrid system of wind power and solar panels, generating around 300 W on average during the summer season. HMP has some equipment in its tents for thermal management (heaters, *COS 8.2*) and air management (vents, *COS 8.3*) but these are not very analogous. Also, *COS 8.5* (ISRU) is currently not populated. Some construction (hand) tools are present at HMP (*COS 8.6*), but they are not very significant in terms of mass. Our models assume that most of the modules involved in a lunar habitat will be designed with easy snap-fit connections and won't therefore require extensive construction activities (cutting, sawing, nailing, bolting, …) and tools, see *COS 8.6*. These assumptions should be revisited in the future as future details on lunar surface access module (LSAM) and habitat design become available.

COS 9: Transportation and Carriers

By far the largest category, in terms of mass, is represented by transportation vehicles on base. Here the correlations between HMP, our pre-HMP estimate and the long lunar mission is excellent, between 9-10 metric tons. Fig. 3.16 shows the mass breakdown for this category.

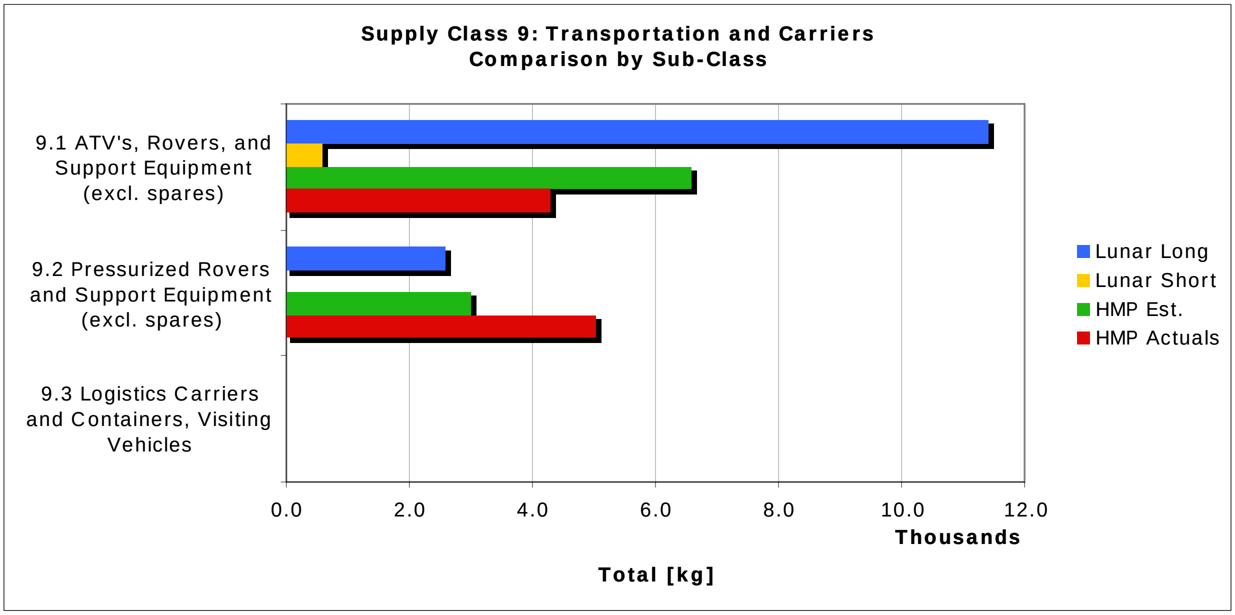

Figure 3.16: COS 9 Comparisons by Sub-class

COS 9.1 captures the ATVs and associated support equipment, excluding spares. The long lunar model assumes a mobility mass of 600 kg per crew member (with 19 crew in this analog model), whereas the actual numbers at HMP include a total of 13 single person ATVs, each weighing between 227 and 325 kg, depending on the model and manufacturer. The short lunar mission has a 600 kg allowance for a couple of Apollo-type lunar roving vehicles (see Fig. 7.2a). Pressurized

vehicles (*COS 9.2*) are estimated at 2,600 kg (two ATV-towed campers) for the lunar mission based on CE&R [7], but the actual Humvee used at HMP is significantly heavier. The estimated mass of the MARS-1 Humvee is 4700 kg (Hummer catalogue value), but the actual vehicle used at HMP is probably heavier as it is a former military Humvee, which still has some heavy shielding involved.[25] Logistics carriers (*COS 9.3*) are a significant mass element on the Space Shuttle, but they have not been accounted for in our lunar models and at HMP. An example of carriers would be pallets and containers that are used for shipping purposes only.

COS 10: Miscellaneous

This class of supply captures public affairs and outreach items (*COS 10.1*) such as flags, patches, and other miscellaneous items (*COS 10.2*) that can not otherwise be classified. We only had to classify 28.5 kg as "miscellaneous" items (< 0.1%) which is a good indication that our COS system (Table 3.1) is useful in distinguishing between supply items in an exploration context.

In totality our actual HMP inventory yielded a mass of 20,717 kg, versus 23,740 kg for the pre-HMP estimate (Table D.1). This is a 15% difference and is suggestive of the level of precision of our current planetary logistics requirements modeling capabilities. However, this conclusion might be somewhat premature as some items have not yet been included in the HMP inventory (e.g. tents) and we suspect that the actual inventory mass at HMP is closer to 25-30 metric tons. Still, with short term lunar mission requirements (Apollo-style) estimated at 10,082 kg and long lunar mission requirements estimated at 36,529 kg we see that HMP falls right in the middle between the two. Some aspects of HMP (short individual stays of 12 days on average) are more like the short-term Apollo-style missions, while others (permanent research infrastructure) are more like the proposed 180 day lunar missions.

3.4 Relational SQL Database

To provide a uniform view of asset management data, we designed a centralized database to support the management and analysis of asset (supply) data at HMP. This database was built using SQL Server 2000. Figure 3.17 shows a snapshot of the user interface to this database.

During our preparation for HMP we found that logistics (i.e. supply class) information needs to be organized and presented in ways that are tailored and customized for particular classes of users. It would be a mistake to create a hierarchical database that presents only a single view. Rather, we believe, that a relational database allows customized reports for the various stakeholders involved in space exploration logistics (see Appendix E, Table E.1):

Astronauts, Mission Operators, Load Masters, Procurers/Vendors, Logistics Modelers

The database allows the user to search for an item by supply class or supply item name. All the attributes associated with each item, such as mass, size, priority level, etc. (as described in Section 3.2) are captured in this database. Figure 3.18 shows the structure of the SQL Database and all the attributes that the database is capable of capturing. Note that not all of these attributes were recorded for each item at HMP. Some of these attributes currently act as placeholders.

[25] The HMP Humvee was driven over winter ice from Cornwallis Island to Devon Island several years ago; since it clearly exceeded the mass and volume capacity of the Twin Otters, see Table 4.1.

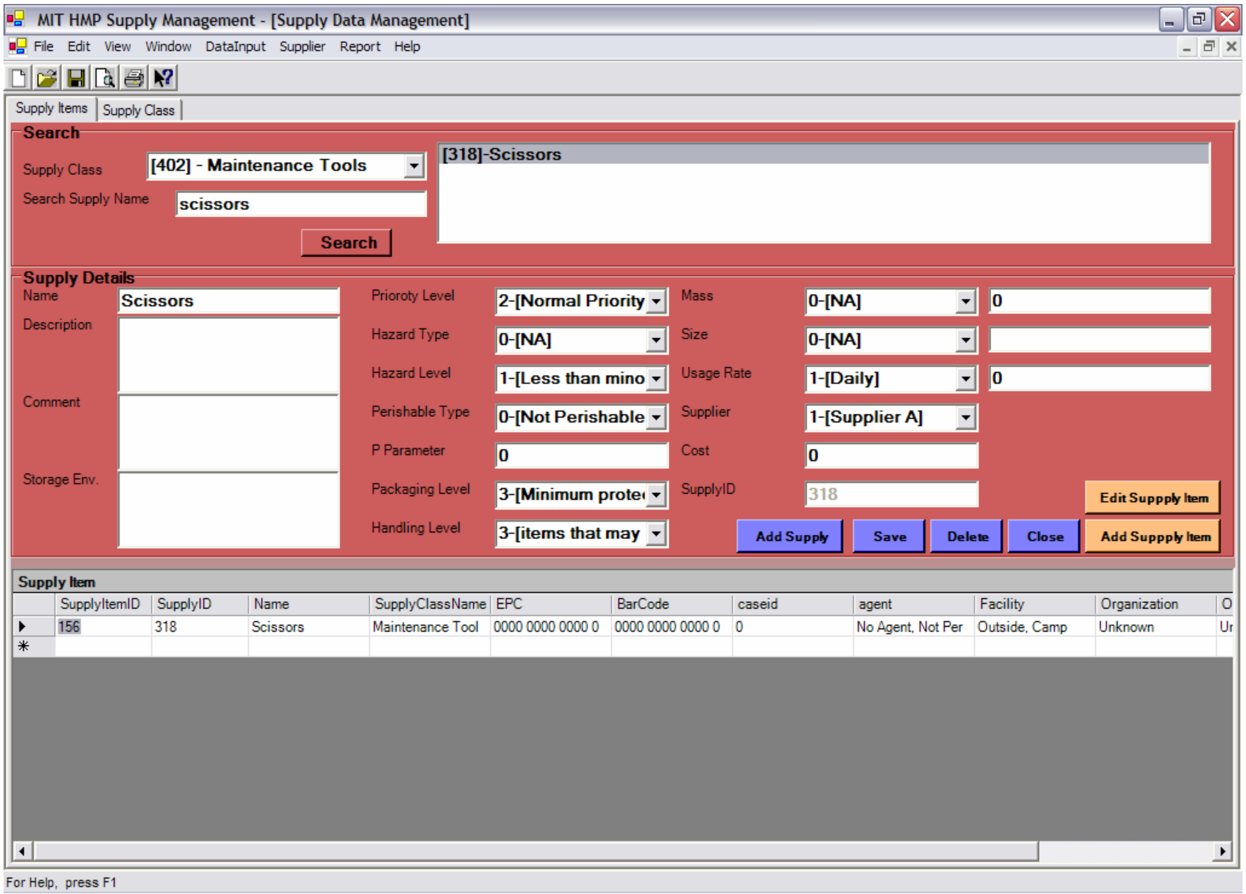

Figure 3.17: HMP Inventory Database – Graphical User Interface (GUI)

To support an automated asset tracking capability, we created an expanded database (Appendix E, Figure E.1) that also captures the various locations, transportation vehicles and agents (individuals) that are involved with the research station. The database was designed to automatically record changes in the *location status* of any supply item that entered or left the MIT tent (or Mess tent during agent tracking) by reading data from the Radio Frequency Identification (RFID) readers located at the entrance to the MIT tent (see Section 5 for a detailed description of the RFID work done at the HMP RS). The location status is reflected in the bottom half of the database, under the ‘Supply Item’ and `Supply Item History’ headings.

Supply Class
Supply Class ID
Supply Class Name
Supply Class Description
Parent Supply Class ID
Supply Class Level
Comments

Supply Type
Supply Type ID
Supply Name
Supply Description
Supply Class ID
Life Span Type ID
Life Span Parameter
Life Span Parameter Units ID
Disposal Type ID
Mass (kg)
Volume (cm3)
Dimensions (cm)
Priority Level ID
Hazard Type ID
Hazard Level ID
Handling Level ID
Packaging Type ID
Flight Support Equipment (FSE) ID
Shipping Environment ID
Storage Environment ID
Origin ID
Source/Supplier ID
Procurement Type ID
Procurement Lead Time (days)
Reprocurement Cost ($FY05)

Common Attributes for all Supply Items

Item
Item ID (e.g. bar code, serial number, EPC)
Supply Type ID
Owner ID
Usage Rate
Usage Rate Units ID
Operational Status ID
Location Status ID
Carrier ID
Facility ID
Parent Item ID
Time Updated
Item Notes

Unique and current Attributes for instances of Supply Items

Item History
Item ID
Time Updated
Operational Status ID
Location Status ID
Carrier ID
Facility ID
Parent Item ID
Item Notes

Record the Tracking History associated with an individual Supply Item

Figure 3.18: SQL Supply Items Database Structure

Of the 2300 items that were inventoried at HMP, approximately 1900 of these items have been entered into the HMP SQL database. We can now query the database to get information on any supply item, such as:

- Where is a supply item now? What's the current status (expired or not)?
- Where has the supply item been? What's the usage rate of a supply type?
- How many supply items are at the research station?
- How many supply items of supply class type "X" are at the research station?
- Find all the supply items with less than X units at the research station?
- How many ATVs are in/out of the base?

We plan on making the relational SQL database available to HMP managers and participants via a password-protected website for planning of the HMP 2006 field season.

4 Remote Base Logistics Network Modeling

4.1 HMP Macro-Logistics Network Model

The previous section focused on the supply items directly and how they can be organized, localized and quantified at the HMP research station itself. This section, on the other hand, will focus on the flow of the supply items to and from the HMP research station (macro logistics). A network model for HMP transportation has been developed for this purpose. First, sources and sinks for supply items, which also represent departure and arrival points in the HMP transportation network have been identified. We will refer to these points as 'nodes' in the transportation network. The nodes are shown in Figure 4.1. The arcs connecting the nodes represent the transportation links between the nodes. As mentioned in Section 2.2 almost all cargo has to travel by air. Both normal and emergency transportation arcs are shown in the network model. Figure 4.1 shows the logistics network model for HMP macro-logistics.

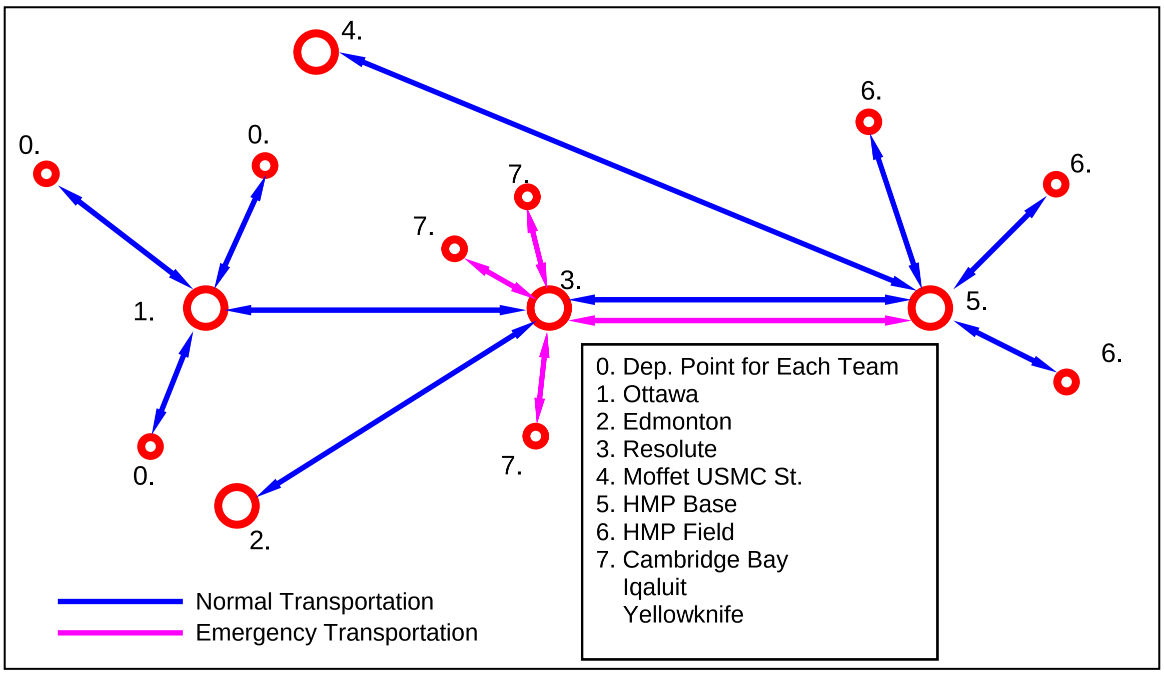

Figure 4.1: HMP Logistics Network Model

The network (Fig. 4.1) starts with the logistics source nodes on the left side. Each team participating in a typical HMP summer campaign has its own departure point (e.g. Montreal for CSA, Boston for MIT, San Francisco for NASA LaRC, Vancouver for SFU, …), designated as node(s) "0". Both crew and cargo then typically fly to Ottawa (node 1) which serves as the main staging point for First Air.[26] First Air ("The Airline of the North") serves Canada's northern destinations and is the main airline connecting communities in Nunavut. First Air's service is reliable, regularly scheduled, partially government subsidized, but still relatively expensive compared to commercial airlines in the U.S. due to the smaller passenger and cargo volumes on

[26] <http://www.firstair.ca>

each route. The main flight from Ottawa (node 1) to Resolute (node 3) takes nearly 7 hours, almost due North, in a modified Boeing 727 (Fig. 4.2a) combination crew/cargo jet. This flight takes place twice a week (Wednesdays and Saturdays), at least during the summer. Typically, stopovers occur in Iqaluit, Nunavut's capital. Landings in Resolute occur on an unpaved runway. An ILS system is in use at Resolute, but is sometimes off-line for maintenance.

Charter flights can also be used to ship crew and cargo to Resolute. One such charter flight occurred in the summer of 2005 between Edmonton (node 2) and Resolute (node 3), via Canadian North[27]. The estimated amount of cargo on that flight was 30,000 lbs. However, this cargo was not only destined for HMP but also for other Arctic research sites. Once arrived at Resolute (node 3), all cargo has to be organized and sorted at the Polar Shelf outdoor staging area (Fig. 4.2b) and warehouse facilities. We found this staging process to be rather ad-hoc (see recommendations in Section 7), yet it seemed to accomplish its purpose. There are three criteria that are implicitly used for staging cargo at Resolute:

1. Lot sizes of roughly ~2400 lbs are made such that they can be conveniently flown from Resolute to HMP aboard Twin Otter airplanes (Fig. 4.2c)
2. Items are prioritized such that safety critical items and crew provisions travel first, typically accompanied by the HMP core team (see Table 2.1)
3. Subsequent items (such as construction supplies and research equipment) are sequenced in a way that work can start or continue at HMP even if supply flights are interrupted due to inclement weather, emergencies, or priority use by other field parties[28]

Once at HMP materials are manually off-loaded at the airstrip. Supply items are then moved around manually or with the help of ATVs (Fig. 4.2d) and two small trailers (micro-logistics). This ensures that supply items are stored at the appropriate place at the research station. Figures 1.2 and 3.7 show the locations around the research station that are typically relevant for micro-logistics: the airstrip, ATV filling station, communications hill, core base camp, and tent city.

The network in Fig. 4.1 shows that an alternate route exists to supply cargo directly to the HMP RS. Airdrops can be arranged on a case-by-case basis. At least one such airdrop occurred in the past, where a C-130 aircraft was dispatched by the USMC from Moffet Field, California. Cargo was secured onto wooden pallets, which were subsequently air-dropped from a low altitude with the help of parachutes. However, this service is not available on a regular bases and route 1-3-5 (Fig. 4.1) is the main trunk along which cargo and crew reach the HMP research station. In the case of medical emergencies, regional towns such as Iqaluit, Cambridge Bay or Yellowknife can be used for evacuation purposes. Micro-logistics from the main HMP base to various field locations (node 6) are discussed in Section 6 on EVA logistics. A potential option for shipping cargo which is not shown in Fig. 4.1 is a barge that provides an annual service for bulk items from Quebec to various coastal communities in Nunavut, including Resolute.

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[27] <http://www.canadiannorth.com>

[28] The philosophy of staging cargo and crew at Resolute is such that the assumption is made that each outbound flight to HMP will be the last flight of the day. This is a prudent assumption as weather conditions, priorities and aircraft availability in the Arctic can change from one minute to the next. We found that an apriori optimized flight plan and crew/cargo-airplane assignment would probably be of little practical use, because the actual circumstances are so dynamic and unpredictable. Flexibility and adaptability appear to be more important than optimality in the current HMP supply chain.

Figure 4.2 (a – top left) Boeing 727 at Ottawa, (b – top right) outdoor staging area at Resolute, (c – bottom left) loading of a Twin Otter, (d – bottom right) ATV park at HMP

Table 4.1 shows the properties of the arcs (vehicles) in the network. Transportation type, capacity, transportation time, cost, and frequency of flights are summarized. A complete model of HMP logistics would require inventory holding costs and capacity in addition to Table 4.1.

Table 4.1 HMP Logistics Arc Properties

	Type	Capacity	TOF	Cost	Frequency
0.D → 1. 0O	Variable				
1.O → 3.R	Airline Jet (Boeing 727)	-	7 hrs	$1800 per person	Twice a week
2.E → 3.R	CSA Chartered Flight	31000 lb	5 hrs	$80000 per FLT	1 per season
3.R → 5.H	Twin Otter	2400 lb	45 min	$2500 per FLT	Max. Observed: 6 FLT a day
4.M → 5.H	Air Force Cargo (C-130 Hercules)	22000 lb	14 hrs	$5000 ~ $10000 per FLT	1~2 per year
3.R → 7	Jet / Helicopter	-	CB (1 hr) Y (2.5 hrs) Iq (3 hrs)	-	-
5.H → 6.F	ATV / HUMVEE	1 p, 100 lb / 3 p, 4000 lb	-	-	Anytime in Field Season

4.2 Flight and Crew Schedule

The duration of the HMP field season for this year (2005) was 29 days. A total of 56 people participated in the HMP campaign, amounting to 683 crew days. The average time which a person spent at the HMP RS was 12.2 days. A total of 29 flights were used to transport crew and cargo between Resolute (node 3) and the HMP RS (node 5). The arc between these two particular nodes is the most interesting arc in the HMP supply chain. There are several factors which make the Resolute-HMP RS arc interesting. The "arc" which connects the two nodes represents Twin Otter aircraft flights whose capacity is on the order of 2400 lbs[29]. This amounts to a capacity of 8 crew members with moderate personal gear. A rule of thumb used for HMP logistics is 300 lbs for each person, including personal gear. Both forward and reverse logistics on arc 3-5 need to be considered. People and scientific research instruments are going in and out of the HMP RS, while consumables and food are supplied in and human and other waste is carried out[30]. Some scientific samples (mainly rock and soil samples from the Haughton Crater) are also shipped out.

We found that during the initial phase of the field season flights are primarily reserved for forward logistics, flying into the HMP RS. Airplanes start at Resolute full of crew and cargo and return to Resolute almost empty. The final phase of an HMP campaign is typically dedicated to reverse logistics – empty flights into HMP and full flights out. During the middle part of the field season most flights transport crew and cargo both to and from the HMP RS according to the field schedule (Table 2.1). Attempts are made to schedule arrivals and departures of research teams in a way such that crew and cargo are efficiently assigned to Twin Otter flights to maximize capacity utilization and minimize the total number of flights and variable transportation costs.

A few other factors make the HMP transportation problem more complex and interesting. There are two flights per week between Ottawa and Resolute – Wednesdays and Saturdays. It should also be noted that staying at Resolute incurs non-negligible staying costs[31], mainly lodging and meals, so a flight schedule that only minimizes the number of flights might not be optimal for total costs, if it causes lots of staying costs. In addition, every Twin Otter flight is uncertain due to changing weather conditions. According to HMP flight planning experience over several field seasons, the probability that a specific flight is not available as scheduled is around 1/3[32]. So any flight schedule should be robust / flexible enough to accommodate external disturbances.

Scheduling of crew (and cargo) transportation between Resolute and the HMP RS is typically carried out by the HMP core team, based on the apriori field schedule (Table 2.1). The planner (typically Dr. Lee himself) collects information from each team about the team's members, cargo weight and expected crew stay duration. With this information, the planner makes a pre-season schedule which hopefully satisfies all the research teams' requirements. Occasionally teams are

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[29] There can be additional cargo loaded in the Twin Otters (up to 3500 lbs at minimum fuel range), but for safety reasons 2400-2800 lbs is used as the operational payload capacity at HMP. Depending on fuel load, there is a tradeoff between range and payload: Source: <http://www.borekair.com/aircraft_twin.htm>

[30] A small incinerator is operated near the airstrip at HMP, but not all waste is disposed through incineration.

[31] This is typically referred to as "inventory holding costs" by logisticians.

[32] The likelihood of launch scrubs at NASA KSC is often modeled as 0.4 based on past experience.

requested to change their duration of stay or arrival and departure dates to improve overall scheduling. Once the field season is underway, transportation of the crew and cargo is carried out according to the pre-determined schedule. However, inclement weather, cargo estimation errors, priority usage by other field parties, and personal emergencies are acting as disturbances to the transportation plan, such that actual flight schedules are dynamically changed to adjust to these factors. Due to this rescheduling process, the total actual number of flights then typically exceeds the initial plan. A comparison between the 2005 pre-season flight schedule and 2005 final flight schedule (actual) is presented in Table 4.2 and Figure 4.2. We can see that the number of Twin Otter flights increased gradually as the HMP field season progressed.

Table 4.2: Evolution of the Twin Otter Flight Schedule over the 2005 field season

PLAN DATE	Expected End of Field Season	Expected Total Number of Participants	Twin Otter Flight (*)	Twin Otter Flight (**)	Etc.
JUN 30th	AUG 12th	56	19	0	-
JUL 10th	AUG 12th	56	23	0	-
JUL 21st	AUG 12th	60	28	2	-
JUL 31st	AUG 9th	58	27	3	(***)2 Helicopter
AUG 7th	AUG 8th	56	26	3	2 Helicopter

Notes: (*) – Contract with Canadian government (PCSP) before beginning of the field season.
(**) – Direct contract with Kenn Borek Air Ltd. Charter Company. The fare for these flights is higher than the pre-season contract rate. (*). (***) – For transportation of media staff and film equipment.

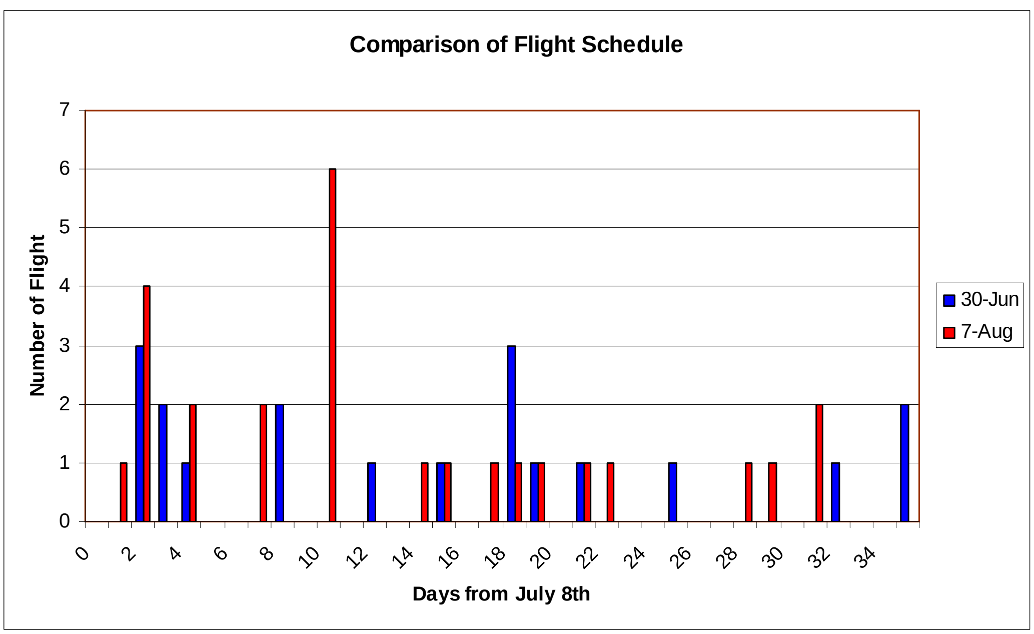


Figure 4.2: Flight schedule comparison: apriori plan (June 30), actual flights (Aug 7)

The actual flight log for the HMP RS-Resolute transportation arc indicates a ~50% increase in the total number of flights between the two nodes as compared to the pre-season plan. Moreover, a pre-season contract with PCSP was not applied to some flights, resulting in higher transportation costs. A detailed log of all flights at HMP 2005 is contained in Appendix F.

4.3 Estimates of Cargo Flow

To completely describe the logistic flow for the HMP campaign, we needed to keep track of all crew and cargo movements, including the weight of the cargo. We succeeded in tracking the majority of the cargo flows but are not sure about the accuracy of some data. We have information about some critical cargo weights (weight of fuel drums, propane gas containers, ATVs etc.) but we were not able to gather full data for others. There are primarily four reasons why we were not able to keep a very precise log of cargo flows in and out of HMP during the 2005 field season:

- Each research team has their own detailed inventory, and inventory procedures are not standardized across organizations. For example some teams included the tare mass of packaging, while others did not. Construction equipment is oftentimes not weighed.
- There is a procedure for staging and weighing cargo at Resolute, but it is rather ad-hoc. Rather than producing an exact estimate, the process merely serves to ensure that the total load does not exceed the ~2400 lbs capacity of a single Twin Otter flight (for flight safety purposes). Cargo and crew supplies to be flown on a Twin Otter flight are grouped together at Resolute, put onto wooden pallets and placed on a scale with a construction type forklift. The load master manually adds up the total weight of the load.
- Manifests for the Twin Otter flights are kept on paper by the pilots, including the names of all passengers and rough description of the load. However, these manifests are primarily kept for legal and invoicing purposes, not for detailed logistics analysis.
- Loading and unloading of cargo at Resolute and at HMP often occurs under windy, cold and generally inclement conditions and under great time pressure. Attempts at carefully documenting cargo are often foiled by the adversity of the situation.

Despite these challenges we estimated the cargo flow, including the estimation of total weights, after the field season had concluded by post-processing of the flight log. The estimated result may not be 100% accurate but we think it can be used as a good basis for campaign logistic planning for following years. This estimation has been added to the flight log we kept during the field season and can be found in Appendix F (right column).

A summary of estimated cargo flows in and out of HMP during the 2005 field season is given in Table 4.3 and Figure 4.3. The total cumulative mass flow into HMP was 50,550 lbs (22,750 kg). This represents an average load of 1740 lbs per Twin Otter flight, corresponding to an average 73% capacity utilization (inbound). The total cumulative mass flow out of HMP was 27,630 lbs (12,430 kg). This represents an average outbound load of 950 lbs, representing an average outbound capacity utilization of 40%. The net gain of mass at HMP during the 2005 field season is estimated to be 22,920 lbs (= 10,300 kg). This number is probably somewhat too high, because we tracked inbound cargo more carefully than outbound cargo. Nevertheless, the overall

conclusion is that more material was brought to HMP than was removed from it. This is clearly true, as 2005 was characterized by substantial construction activity (three new tents/modules were erected, see Fig. 2.3). We also suspect that a number of teams bring more equipment than they remove, because they intend to reuse equipment in future years. We found that expensive and sensitive equipment, such as communications electronics, telemedicine kits, RFID transceivers …, is generally removed from HMP at the end of the field season for the following reasons:

- electronics would likely be damaged by the harsh subzero winter conditions
- many researchers need their expensive equipment for other projects during the year
- equipment is often brought back for analysis, repair and upgrade for future field seasons

What is essentially left behind are "inert" items such as tools, furniture and dry foods which are not generally harmed by the Arctic winter. Based on the amount of net inflow into HMP we can establish an upper bound for the likely total amount of mass currently present at HMP. If we assume that each of the last 9 active field seasons has brought in a net surplus of 10 metric tons, we estimate that there can be no more than 90 metric tons of man-made materials at HMP at the present time.[33] In Appendix C we show an inventoried total mass of 20.7 metric tons, plus an estimated 7 metric tons for the erected structures that were not included in the inventory. Thus, a lower bound for the amount of imported mass currently present at HMP is 27 metric tons.

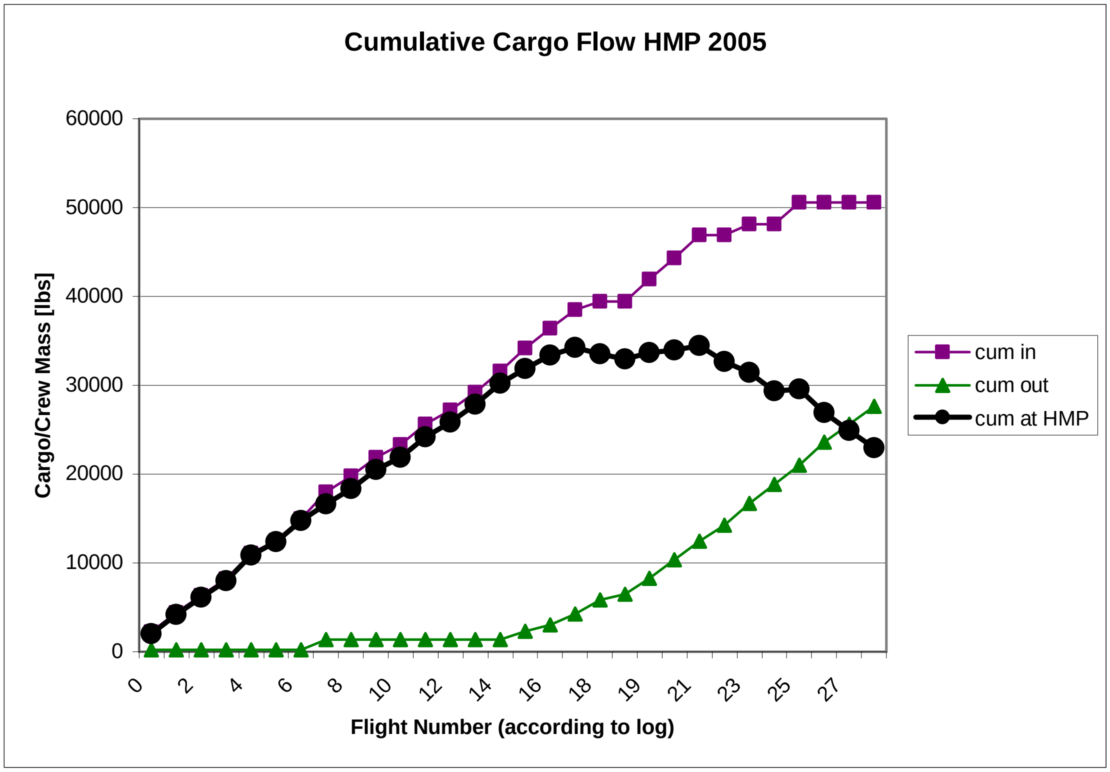


Figure 4.3: Cumulative mass flow in and out of HMP for the 2005 campaign

[33] Early field seasons in the 1997-2000 timeframe likely had many fewer flights involved, on the other hand we did not account for materials that were air-dropped by C-130s in previous years in establishing this upper bound.

The total mass flow associated with the 56 personnel flown in and out of HMP (assuming 300 lbs per person) is 16,800 lbs. This accounts for the body mass of individuals, full clothing and personal gear, including individual tents. We assume that all personal gear is removed from HMP and, thankfully, no individuals were lost. The conclusion is that 33%, i.e. exactly one third of the inbound cargo flow is due to individual researchers, whereas two thirds are due to construction equipment, vehicles, spares, food and other consumables as well as scientific equipment. Of the outbound cargo, personnel and their gear account for 61%, i.e. nearly two-thirds of the transported mass, whereby the remaining third was due to scientific equipment, various waste, empty fuel containers and broken equipment (e.g. ATVs) being returned.

Table 4.3: Summary of Cargo Flow Estimates in and out of HMP (2005)[34]

flight number	mass in [lbs]	mass out [lbs]	cum in [lbs]	cum out [lbs]	cum at HMP**
0	2200	200	2200	200	2000
1	2200	0	4400	200	4200
2	1900	0	6300	200	6100
3	1900	0	8200	200	8000
4	2850	0	11050	200	10850
5	1500	0	12550	200	12350
6	2410	0	14960	200	14760
7	3050	1200	18010	1400	16610
8	1770	0	19780	1400	18380
9	2100	0	21880	1400	20480
10	1400	0	23280	1400	21880
11	2300	0	25580	1400	24180
12	1640	0	27220	1400	25820
13	2000	0	29220	1400	27820
14	2380	0	31600	1400	30200
15	2560	900	34160	2300	31860
16	2240	750	36400	3050	33350
17	2100	1200	38500	4250	34250
18	900	1600	39400	5850	33550
18.5*	0	600	39400	6450	32950
19	2530	2400	41930	8250	33680
20	2400	2100	44330	10350	33980
21	2610	2100	46940	12450	34490
22	0	1800	46940	14250	32690
23	1200	2470	48140	16720	31420
24	0	2100	48140	18820	29320
25	2410	2185	50550	21005	29545
26	0	2625	50550	23630	26920
27	0	2000	50550	25630	24920
28	0	2000	50550	27630	22920
final			**50550**	**27630**	**22920****

* refers to a separate, chartered helicopter flight, ** only 2005 net influx of mass to HMP

[34] based on the flight log in Appendix F

4.4 Optimization and Suggestions for Improvement

As was stated in the previous section, the transportation arc that has the largest potential for improvement is the one between Resolute and the HMP RS (route 3-5 in Fig. 4.1). Once the logistics schedule in this arc is determined, logistic flows between other nodes are practically fixed without much difference in the cost.

The optimization over the whole HMP logistics network might be an interesting, but complex problem. For this year, we built an idealized transportation schedule between HMP and carried out calculations for the minimum number of the Twin Otter flights that would be required to transport the same amount of crew and cargo mass as shown in Figure 4.3 and Table 4.3. The result is that a "boxcar" type logistics profile is generated. A boxcar profile is one where the number of researchers on base is essentially constant over the duration of the field campaign. This is similar to future (initial) human Moon and Mars exploration campaigns where 3-6 team members are likely to arrive and depart together or follow a regular rotation schedule. Instead, the current crew profile at HMP looks more like a triangular distribution, see Fig. 4.4. In generating an equivalent boxcar profile for HMP we made the following assumptions:

- The staying time for each participant is the same
- Except for the initial and final flights, both incoming and outgoing flights have passengers, and the number of incoming and outgoing passengers is identical.
- It is assumed that cargo flights are done separately at the beginning and end of the season. The total number of cargo flights is 8.

The expected and actual number of crew at the HMP RS at the beginning and end of the season is plotted along with the described "boxcar" profile in Figure 4.4. According to the 2005 actual flight schedule, the total number of crew-days for this season was 683 and the total mission duration was 29 days. When we create an equivalent "boxcar" type profile to match with this year's flight data, we can calculate the profile presented in Table 4.4. The total number of flights for this profile is 20. Recall that the actual number of flights for the 2005 field season was 29 (including the helicopter flight), so when we compare the two numbers, this "ideal" flight schedule could save up to 33% in terms of number of flights and therefore transportation costs.

Table 4.4: Calculation of "boxcar" profile for HMP logistics

2005 Field Season Result	
Total Crew Days	683
Mission Days	29
Boxcar Profile Parameters	
Total Number of Participants	56
Staying Duration in Days	12
# of crew @HMP, @ any time	24
Flight Requirements	
# of Crew Flights	12
# of Cargo Flights	8
# of Total Flights	20

The number of 20 flights, segregated by crew and cargo, would indeed be able to carry the 50,000 lbs of total inbound cargo flow (Table 4.3) that occurred in 2005, provided that each flight be loaded to capacity. It should also be noted, however, that this is only a lower bound for the number of flights needed, and therefore an upper bound for the potential transportation cost savings. Assuming a cost of $2500 per Twin Otter flight (round trip), potential savings would be on the order of $25,000 per field season. The "boxcar" profile (Fig. 4.4), however, does not account for any kind of constraints for arrival / departure times of specific participants or cargo, which do exist in reality. In addition, even with a well-optimized flight schedule at the beginning of the season, there exist large uncertainties which may disrupt the pre-optimized flight schedule (see Section 4.1). So, in this type of flight scheduling, where high levels of uncertainty exist, "robustness" of the flight schedule solution is as important as the "optimality" of the solution. So, if we wanted to carry out flight scheduling optimization for HMP, we would have to either include some terms related to the "robustness" in the objective of the optimization or perform an a posteriori sensitivity analysis of the optimized solution.

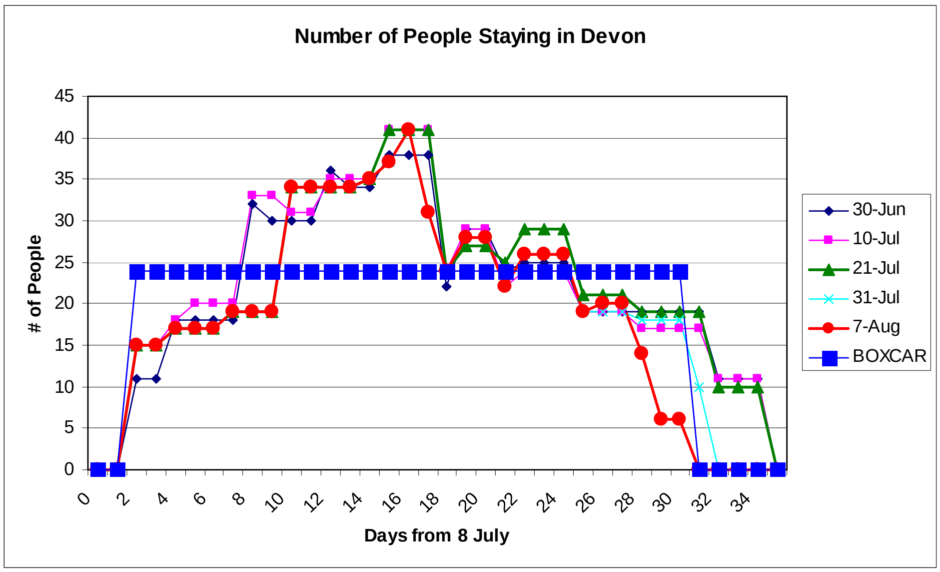


Figure 4.4: Crew profile at HMP RS: apriori plan (30 Jun), actual log (7 Aug), various intermediate plans during the field season (10 Jul, 21 Jul, 31 Jul), (BOXCAR) equivalent boxcar profile if the number of participants at the research station were kept constant

The flight scheduling for the 2005 field season was done by human heuristics based on past years' experiences. As shown, the final number of flights was about 50% larger compared to the schedule at the beginning of the season. We found that the increase was mainly due to the inaccuracy of the cargo weight prediction and uncertainty of the weather. Using the current scheme, HMP campaigns have been executed without major problems. Nevertheless, there is some room for improvement (see Section 7 for specific recommendations).

5 Agent and Asset Tracking (RFID)

The previous sections summarized our findings in terms of actual supply items present at the HMP RS as well as how these are transported into and out of the base (macro-logistics). Experiences on past and present human spaceflight programs (e.g. STS, ISS) show that micro-logistics must also be considered. Micro-logistics comprises the management of supply items within the base and its immediate vicinity (< 100 km). This section discusses our research into tracking of both crew ("agents") and cargo ("assets") while on base.

5.1 Current state-of-the-art for asset tracking on ISS

Asset tracking on the International Space Station (ISS) relies on a barcode based system that interfaces to the Inventory Management System (IMS). The IMS database is a SQL Server 2000 database with a JAVA Graphical User Interface, see Fig. 5.1, which was jointly developed by NASA and the Russian Space Agency (RSA). Presently, approximately 20,000 items are barcoded before launch and then are tracked in IMS once on orbit. Critical information about each item, such as a part number, serial number, barcode, proper name, dimensions, owner, etc. is entered into IMS by U.S. or Russian flight controllers before the item arrives at the ISS. Once on-orbit, the crew uses handheld barcode readers to record movement of the item around the ISS.

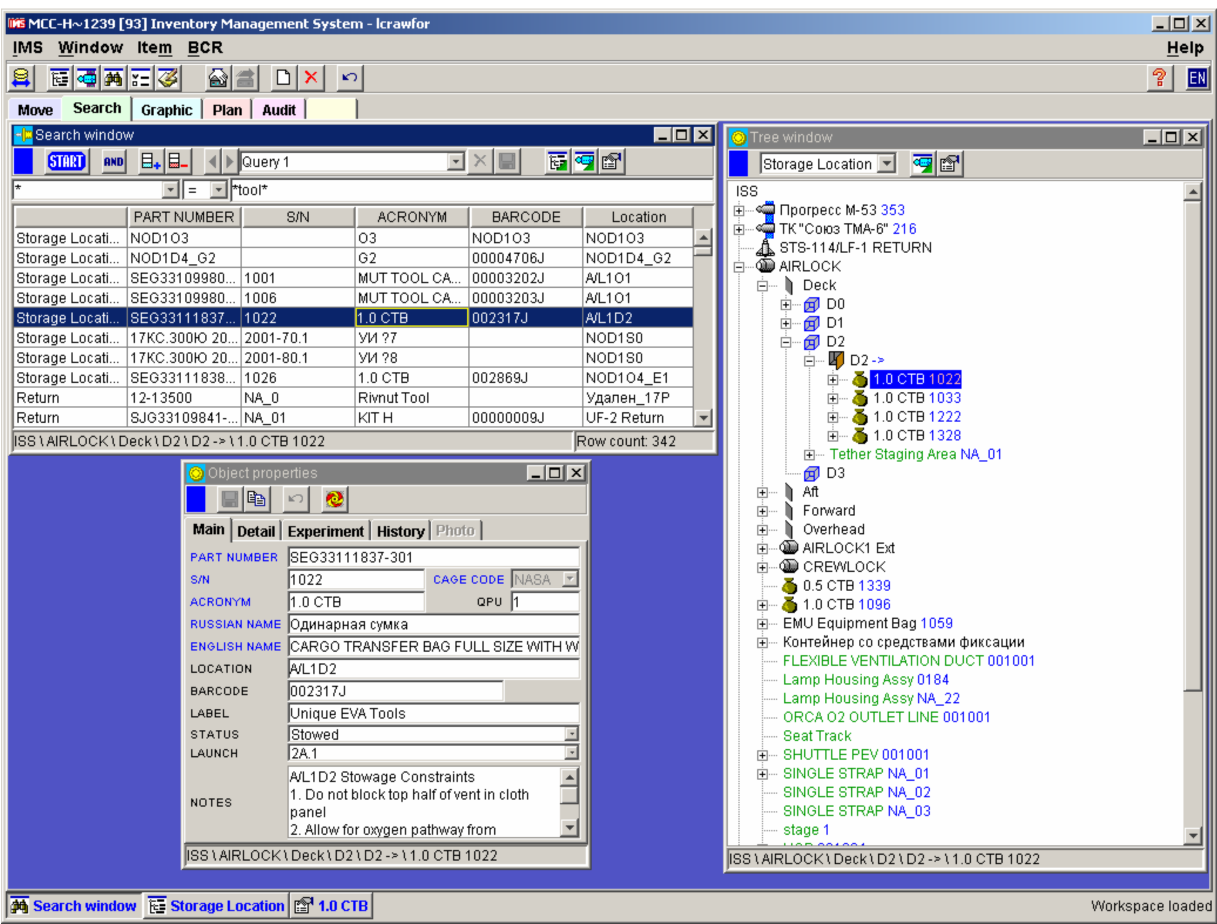


Figure 5.1: Screen view of ISS Inventory Management System (IMS), Source: NASA JSC

Updates are made in IMS on a daily basis by either the ISS crew, the Inventory and Stowage Officer (in Houston) or the Russian Inventory and Stowage Specialist (in Moscow). The crew is allotted 20 minutes each day to update the IMS database either using the handheld barcode reader or manually entering changes on their laptop computers. The architecture of this system is shown in Figure 5.2.

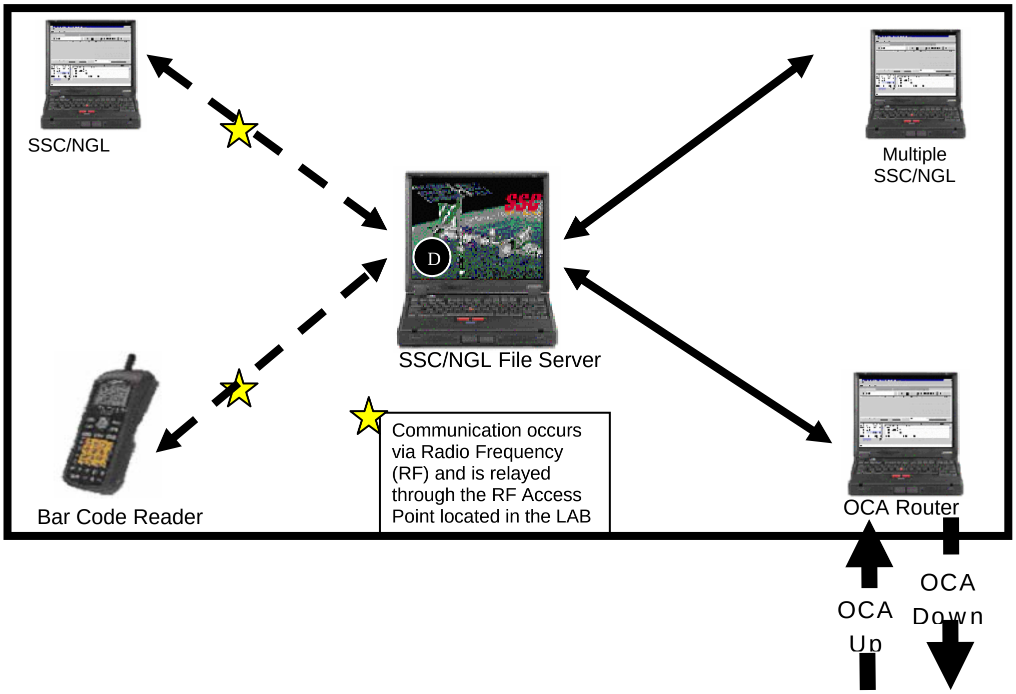


Figure 5.2: IMS onboard architecture for ISS asset tracking, SSC = station support computer, NGL = new generation laptop, OCA = orbital communications adapter

IMS records a history for each item so that the crew or ground controllers always have the ability to see what has been changed on each item since it was initially entered into the database.

Using a barcode based system for inventory management is reliable, but very labor intensive so occasionally an IMS update is missed and an item's status becomes unknown. On average 3% of the items in the IMS database are listed as "lost". This means that an item was not in the location that it was showing in IMS the last time the crew looked for it. If a critical item is listed as lost the mission control team has to decide whether to allocate critical crew time to continue looking for the item or, if there is a spare on the ground, to re-fly the item on an upcoming resupply mission.

Emerging technologies, such as Radio Frequency Identification (RFID, see Section 5.2), show great promise for improving asset tracking for space exploration. The following sections give some background on RFID and explain the RFID work done by our team at the HMP RS during the 2005 field season.

5.2 RFID Technology Overview

Radio Frequency Identification (RFID) is a generic term for technologies that use radio waves to automatically identify people or objects. There are several methods of identification, but the most common is to store a serial number that uniquely identifies a person or object, and perhaps other information, on a microchip that is attached to an antenna, which in turn is attached to the object or person.

The chip, which is less than 5 mm across, activates a signal when it approaches an electronic reader. Though RFID technology has been around since World War II, when it helped ground soldiers identify fighter airplanes as friend or foe, the cost of developing it has been prohibitive. Now, thanks to advances in technology, RFID is here to stay. Business experts predict that RFID chips will be found in thousands of products by 2010, and that the technology will revolutionize supply chain management, manufacturing, and retail efficiency.

5.2.1 The Basics of RFID

Automatic identification (auto ID) technologies help machines or computers identify objects by using automatic data capture. RFID is one type of auto ID technology that uses radio waves to identify, monitor, and manage individual objects as they move between physical locations. Although there are a variety of methods for identifying objects with RFID, the most common method is by storing a serial number that identifies a product and its related information. RFID devices and software must be supported by an advanced software architecture that enables the collection and distribution of location-based information in real time.

An RFID system consists of tags and readers. RFID tags are small devices containing a chip and an antenna that store the information for object identification. Tags can be applied to containers, pallets, cases, or individual items. With no line-of-sight requirement, the tag transmits information to the reader, and the reader converts the incoming radio waves into a form that can be read by a computer system. An RFID tag can be active (with a battery) or passive (powered solely by the signal strength emitted by the reader).

Active Tags

- Can be read from a long-range distance of more than 100 feet.
- Are ideal for tracking high-value items over long ranges, such as tracking shipping containers in transit.
- Have high power and battery requirements, so they are heavier and can be costly.

Passive Tags

- Can only be read from a short-range distance of approximately 5–10 feet.
- Can be applied in high quantities to individual items and reused.
- Are smaller, lighter, and less expensive (and therefore more prevalent) than active tags.

5.2.2 How RFID technology works

Figure 5.3: Key elements of an RFID system

- An interrogator emits RF waves, which are picked up by tags nearby
- A tag modulates the signal and responds with its unique identifier
- The interrogator filters the responses to identify events like tag arrivals and departures
- These events are communicated to enterprise middleware software which understands the business process impact of this activity.

5.2.3 RFID, Smart Cards, and Other Form Factors

RFID technology is currently being used in conjunction with smart card technology in the financial industry, primarily in Europe. Financial institutions are issuing smart cards to record personal finance information such as account balances. RFID technology is also being used in other forms such as key fobs, bulk metal tags, garment disks, and even metal nails that can be driven into pallets.

5.2.4 RFID and Barcodes

Although it is often thought that RFID and barcodes are competing technologies, they are in fact complementary. The primary element of differentiation between the two is that RFID does not require line-of-sight technology. Barcodes must be scanned at specific orientations to establish line-of-sight, such as an item in a grocery store, and RFID tags need only be within range of a reader to be read or 'scanned.' Although RFID and barcode technologies offer similar solutions, there are significant advantages to using RFID:

- Tags can be read rapidly in bulk to provide a nearly simultaneous reading of contents, such as items in a stockroom or in a container.
- Tags are more durable than barcodes and can withstand chemical and heat environments that would destroy traditional barcode labels.

- Tags have read and write capabilities and can be updated. Barcodes contain static information that cannot be updated unless the user reprints the code.
- Tags can potentially contain a greater amount of data compared to barcodes, which commonly contain only static information such as the manufacturer and product identification.
- Tags do not require any human intervention for data transmission whereas barcodes generally do.

It is easy to see how RFID has become indispensable for a wide range of automated data collection and identification applications. With the distinct advantages of RFID technology, however, comes an inevitably higher cost. RFID and barcode technologies will continue to coexist in response to diverse market needs. RFID, however, will continue to expand in markets for which barcodes or similar optical technologies are not as efficient.

5.2.5 The Use of RFID

Although RFID is a proven technology that has existed since before World War II, it took many years for large scale implementation to occur in the United States. The implementation eventually included freeway toll booths, parking areas, vehicle tracking, factory automation, and animal tagging.

In 1998, researchers at the Massachusetts Institute of Technology (MIT) Auto-ID Center began to complete global research on RFID. The Auto-ID Center focused on:

- Reducing the cost of manufacturing RFID tags.
- Optimizing data networks for storing and delivering large amounts of data.
- Developing open standards for RFID.

The work of the Auto-ID Center has helped to make RFID technology economically viable for pallet and carton-level tagging. The Auto-ID Center closed in October 2003, transferring all its RFID technology and information to the EPCglobal organization.

The most common application of RFID technology today is for tracking goods in the supply chain, tracking assets, and tracking parts from a manufacturing production line. Another common application is for security—RFID is used to control building access and network security, and also for payment systems that let customers pay for items without using cash. As technological advancements in RFID lead to an even higher level of data transmission—in addition to significantly lower cost—RFID technology will become ubiquitous within the supply chain industry and other industries, increasing overall efficiencies and dramatically improving the return on investment (ROI).

Although deploying RFID solutions that are connected to business-management solutions will be straightforward plug and play, the solutions won't show their full potential until RFID has been widely adopted.

5.2.6 RFID Global Standards

As RFID technology continues to expand, the need for establishing global standards is increasingly apparent. Many retailers have completed RFID trials within their supplier communities, adding pressure on manufacturers and suppliers to tag products before they are introduced into the supply chain. However, manufacturers cannot cost-effectively manage RFID tagging mandates from disparate retailers until global standards are established. This process requires the creation and acceptance of data standards that apply to all countries, and it requires scanners to operate at compatible frequencies.

EPCglobal is a member-driven organization of leading firms and industries focused on developing global standards for the electronic product code (EPC) Network to support RFID. The EPC is attached to the RFID tag, and identifies specific events related to the product as it travels between locations. By providing global standards on how to attach information to products, EPC enables organizations to share information more effectively. The vision of EPCglobal is to facilitate a worldwide, multi-sector industry adoption of these standards that will achieve increased efficiencies throughout the supply chain—enabling companies to have real-time visibility of their products from anywhere in the world.

5.2.7 RFID Solution Architecture

There are efforts underway to create a reliable, cost-effective software platform to facilitate and support RFID-enabled solutions. The following illustration provides a high-level view of a comprehensive RFID solution architecture. Adoption of such an architecture for exploration logistics is becoming a real possibility.

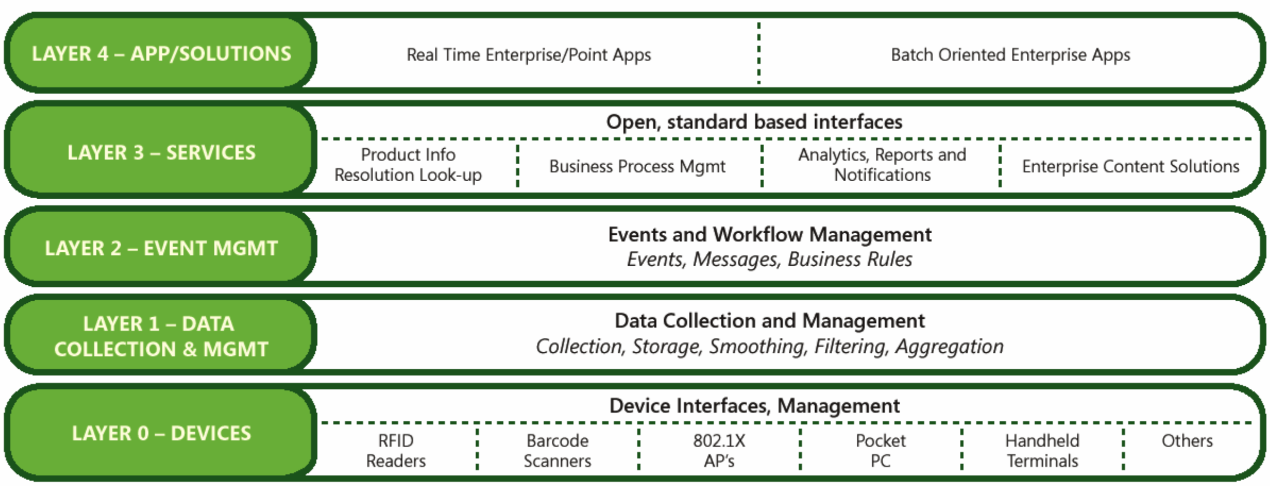


Figure 5.4: RFID Solution Architecture

Layer 0: Devices
The devices layer consists primarily of devices that are on the periphery of the RFID-enabled system, such as RFID readers by third-party manufacturers, 802.1x access points for wireless local area networks (LANs), barcode readers, and other related technologies that add value to the overall solution architecture.

Layer 1: Data Collection and Management
The data collection and management layer consists of the basic operating environment and foundation of the solution architecture. It includes hardware, operating system(s), network(s) and other infrastructure components across the distributed implementations. This layer also includes:

- Deployment and management tools for the various readers and devices in the Devices layer.
- Adapters and interfaces that interoperate with the readers in the Devices layer.

Layer 2: Event Management
The event management layer and the layers above it enable the business processes and solutions that leverage real-time data generated by the RFID technology layers below. This layer also provides the structure for integration across multiple facilities and partners, and interoperating with the EPC Network components in the event it becomes a customer requirement.

Layer 3: Services
The services layer provides services that are implemented as the “abstraction” of the layer or layers below it, and can be implemented as application programming interface (API) services and web services. For example, the product information resolution look-up service might be implemented as a Web service to extract information from the product catalog database located in layer 2. Various business process services such as business intelligence, analytics, and query reporting can also be implemented into this layer.

Layer 4: Applications Solutions
The applications solutions layer uses the services, data, and tools provided by the layers below it to implement application solutions that drive business processes for the end user.

5.3 RFID Experiment Objectives and Procedures

RFID is relatively new, so questions remain about the technology itself and how best it can be applied to manage a remote base. Our 2005 HMP field-season objectives therefore included experiments to test the benefits and limitations of the technology, as well as a less formal effort to monitor base activity and understand how asset tracking might improve operations.

Our questions with respect to the former included: What are the actual benefits and costs of using an RFID system to track assets at a remote site in terms of time saved, accuracy, and system complexity? What additional requirements might be needed to make such a tracking system worthwhile? How should the architecture of the RFID system be designed? Are there interference issues with respect to RF waves? How can the accuracy of the system be improved in the field? What range is typical in the field and what kinds of tags are best to use?

Our questions with respect to applications of the technology were of a different sort. They included: What items are most in need of tracking at a remote base? At what level should these items be tracked? Where and how should this information be presented? Can asset tracking be incorporated into other aspects of base-management? If so, where best does it fit in?

In order to address these questions, we took *a three-pronged approach*. First, we established a formal experiment to compare the benefits and drawbacks of stowage management using RFID to stowage management using traditional barcode techniques. Second, we developed two informal technology demonstration experiments, using different kinds of RFID technology, to track agents and assets through parts of the base. Finally, we made observations about how and when people looked for supplies, what kind of supplies they needed and, generally what kind of help they needed with managing base assets. The details of these experiments and results are described below.

Based on the current available RFID technologies, we purchased two set of RFID equipments from Alien Technologies.

- ALR-9780 High Performance, 4-port UHF passive reader with a reading range up to 30 feet and 2000 passive tags, 4 antennas
- ALR-2850 Long-Range, battery assisted passive reader, 30 Battery assisted tags with a reading range of 60 feet, 2 antennas

5.3.1 Formal Gate Experiment Description

The formal experiment compared the time savings and accuracy of RFID versus bar-coding systems (as currently in use on the ISS, see Section 5.1) in tracking assets. To do this, an RFID gate was set up at the entrance of the MIT tent (see Fig. 2.3), and volunteers were asked to walk through the gate and store objects in a specified way. The gate was composed of four one-watt, circularly polarized antennas, operating at 915 MHz and arranged in a rectangular pattern. The antennas were installed on tripods, bungeed to the tent roof, and placed in a zip-lock bag on the floor (see Fig. 5.5).

We asked a total of 10 volunteers to run through the following procedure six times:

1. Pick up a box filled with tagged items
2. Walk through the gate
3. Put the box down
4. Take the items out* and sort them from biggest to smallest on a table
5. *If using bar-coding, scan items before laying them down

For each of the six runs we varied one of the following three parameters:

1. Tracking system: Barcode vs RFID
2. Active Antenna Number: 2 vs 4
3. Number of items: 10 vs 20

For each run, we recorded both the total time taken and the accuracy of the system. In this way we hoped to compare system time-saving and system accuracy with respect to antenna number (radio power and orientation), number of items, and tracking technology. The results of the experiment are discussed in Section 5.4 below.

Figure 5.5: One of our volunteers, Samson Simeon, carrying out one run of the formal RFID experiment. Four antennas are mounted (left, right, top, bottom) forming a gate.

Figure 5.6: Items to-be-tracked aligned in order on a work bench inside the MIT tent

5.3.2 Inter-Module Transfer and ATV Tracking Experiment Description

In addition to the RFID gate experiment, we set up a gate to monitor the flow of people past a given doorway, as a potential precursor to a base-wide tracking system. This system included

four 1-watt antennas set up at the entrance to the Mess Tent (Fig. 2.3), and multiple passive tags handed out to all HMP participants, see Fig. 5.7.

Figure 5.7: Example of a passive RFID tag and associated bar-code handed out to each HMP participant for the RFID gate experiment.

The experiment was fairly straightforward: We asked participants to place tags in their pockets and the system recorded a hit when they passed the mess-tent door. We wrote a simple application to store this information in a data-base with which we could recreate the times when a given participant (or asset eventually) passed that location. We let this experiment run continuously for three days. Figure 5.8 shows Mike Li setting up the system at the entrance of the Mess tent.

Figure 5.8: Setup of the inter-module transfer system at the Mess tent entrance

The ATV tracking experiment was similar to the Mess-tent experiment, however in this case ATVs were tracked rather than people, and a different tag-type and system configuration was implemented. The system used battery-activated passive tags rather than strictly passive tags, and

the antennas were placed outside along the road to the airstrip, see Figure 5.9. The reader was connected to the camp intranet via a portable communications system provided by Dr. Steve Braham (SFU).

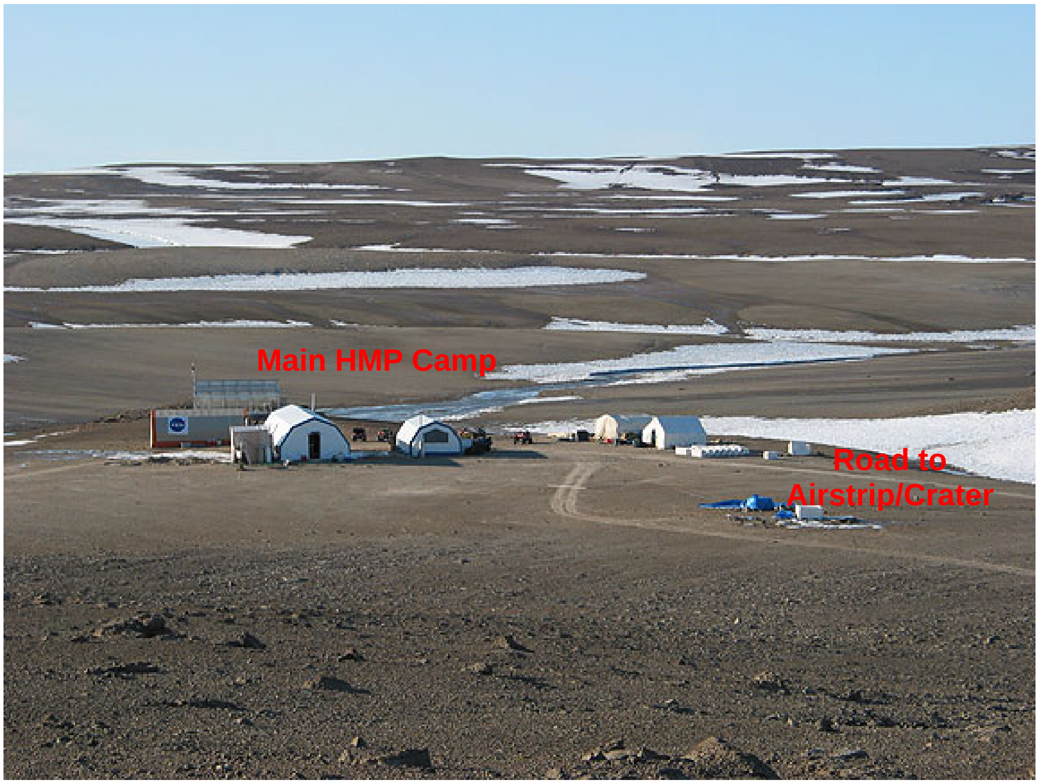


Figure 5.9: HMP research station (in a pre-2005 configuration) with airstrip road clearly shown at the lower right

The main reason for the extra link was that the ALR-2850 system radiates at 2450 MHz, which may have interfered with base communications. Even the 915 MHz readers interfered with the safety radios when they passed nearby. These issues are fairly important, and will have to be worked around in the design of the communications infrastructure of a future planetary base. They are also part of the trade-off with developing tracking and logistics management systems that radiate RF, although, it is possible to insulate the signals for specific applications.

Once the system was set up on the road leading to the airstrip, we tested multiple mounting locations for the tags on the ATVs. Figure 5.10 gives a summary of the experiment and provides a picture of this test. Finding a suitable tagging location turned out to be more difficult than expected for two reasons. First, one of the antennas provided did not work, so we had less range than expected. Second, because ATVs were going in two directions it was hard to find a location that was close to the reader at all times. We ended up using two tags for each vehicle, mounted on either side of the wheel rim.

Figure 5.10: Outdoor RFID All-Terrain Vehicle tracking experiment

Once the system was set up, the tags were mounted, and each vehicle identified, we let the experiment run from 7/26 to 8/1, and continuously for three days within this period. The software application that we created allowed us to identify when a given vehicle was entering or leaving the base depending on whether the event was even or odd. This method was not 100% accurate however, but did give a better picture of ATV usage.

5.3.3 Software Application: Smart-Check Out

We also developed an application to scan and record supplies inside the Humvee vehicle, the analog of a pressurized rover at HMP. This list of items can then be compared with a list of critical supplies required for an exploration sortie in real time to instantaneously assess the readiness for an exploration mission and give a missing items report. Such a "smart checkout" of a vehicle could be done with handheld RFID readers in the future, significantly shortening the time required to ready a vehicle and set of equipment for a scientific traverse (see Section 6). Due to the fact that the Humvee was not available while we were at HMP RS, we didn't carry out the experiment.

5.4 RFID Experimental Results

5.4.1 Formal Gate Experiment Results and Discussion

As expected, the accuracy of the RFID system was below that of bar-coding, but the speed was much higher. When fewer items were transported through the RFID gate at once, the read accuracy was higher and when more antennas were used, accuracy was also improved. Doubling the number of items to manually scan (barcode) generally meant more than doubling the time required, while the time required for RFID was independent of the number of items.

Specifically, we recorded a total of 120 data points. Table 5.1 shows a snapshot of some of the raw data recorded for the formal RFID gate experiment conducted in the MIT tent (see Section 5.3.1). As indicated, for each run, we recorded the number of items that the system recorded, the resulting accuracy in percent, and the total time in seconds. A screen view of the software application (layer 1) that was programmed to conduct the experiment is shown in Fig. 5.11.

Table 5.1: Sample data results for the formal RFID gate experiment

Exp #	Name	Run #	RFID # rec.	RFID Acc.	RFID Time (sec)	BC # rec.	BC Acc.	BC Time (sec)
1	Richard	1	14	70%	36	20	100%	95
1	Karin	2	16	80%	78	20	100%	232
1	Aginesh	3	15	75%	64	20	100%	154

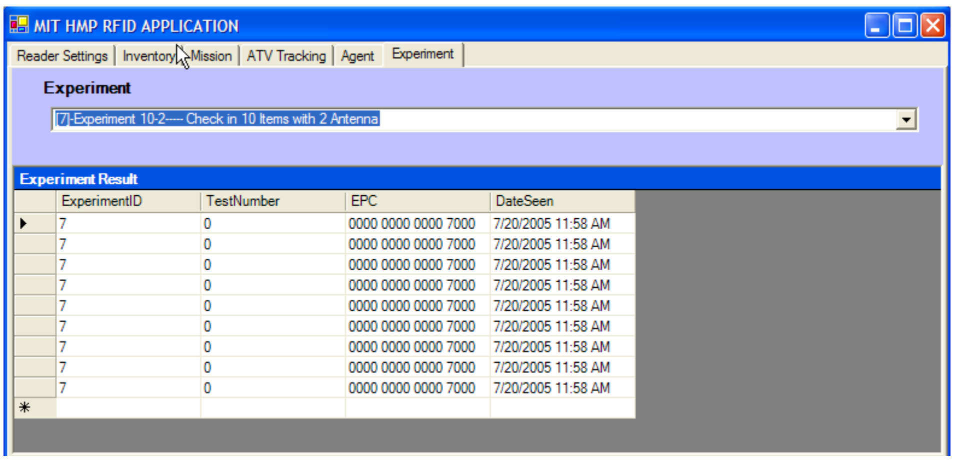


Figure 5.11: Software - Accuracy and Time Efficiency of RFID vs Barcoding

Figure 5.12 shows the mean time and standard deviation for all the experiments. As can be seen, the bar-coding system took nearly twice the amount of time as the RFID system for ten items, and about three times the amount of time for twenty items. This trend suggests that as the number of items tracked increases, the time-savings for an RFID system become increasingly significant. This makes intuitive sense, since barcoding requires extra labor, and can become increasingly difficult as the number of items increases.

It should also be noted that the standard deviation in terms of time required to conduct a run is significant, caused by differences between individual test subjects. The barcode system on average had a greater variance than the RFID system, with a significant increase in standard deviation when we increased the lot size to 20 items. This result also makes sense, since the time taken to record each item into the system depended somewhat on the test subject's speed and familiarity with barcoding technology. Moreover, this also suggests that RFID systems may have the additional benefit of more accurately allocating time to logistics activities. If the time it takes to sort and store assets is known more accurately using RFID, it could help manage other aspects of life at a remote research station.

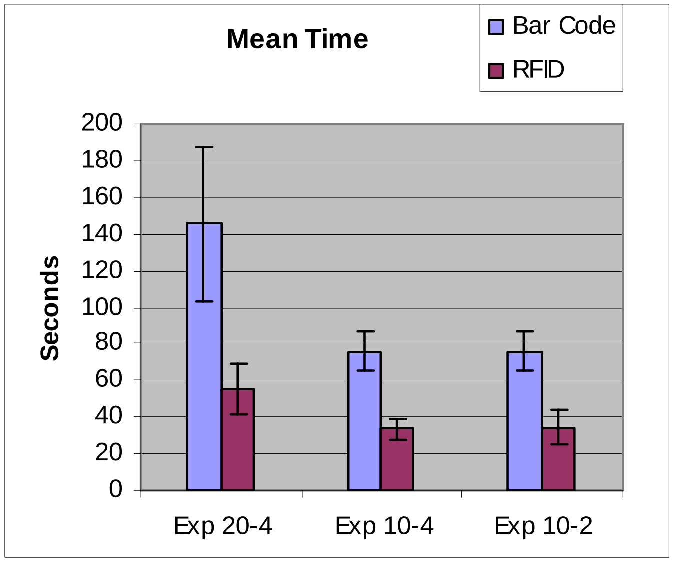


Figure 5.12: Average time and standard deviation for formal RFID gate experiment. Exp 20-4 (20 items, 4 antennas), Exp 10-4 (10 items, 4 antennas), Exp 10-2 (10 items, 2 antennas). One standard deviation (σ) indicated by error bars

Figure 5.13 illustrates a similar plot of average read accuracy (% recorded) versus RFID experiment, with standard deviation included. Again, the basic form of the results is as expected. The barcode system was 100% accurate because participants continue to scan items until an indicator tells them that it has been recorded. For the RFID system, however, such an audio signal does not exist since 10 or 20 items are being read at once. We found that the average read accuracy of the RFID system was between 70-85%. When fewer items were tracked at once, slightly better accuracy resulted, and four antennas recorded items with more accuracy than two.

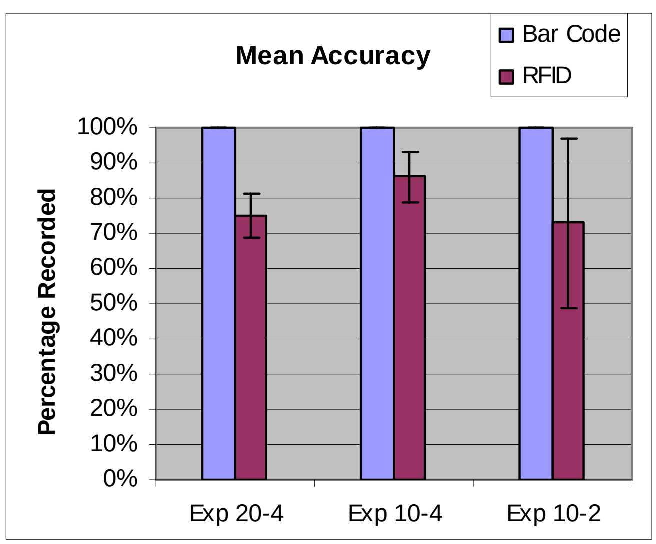


Figure 5.13: Average read accuracy and standard deviation for formal RFID gate exp.

Again, the variance in the data sets gives useful information. Although the mean accuracy of the 10-item/2-antenna experiment (10-2) and 20-item/4-antena experiments (20-4) were roughly the same, the former exhibited much higher variance. This suggests that the number and orientation of RFID antennas has a critical impact on read accuracy and variance. It will be critical for future space vehicles (e.g. the crew exploration vehicle CEV) and habitats that the number, location and orientation of RFID antennas is carefully chosen and integrated in the design early on.

Some caveats with respect to the RFID experiments should be noted.

First, we had each participant sort the objects after walking through the gate. We did this to ensure that the comparison between barcode and RFID technology was fair. In reality, we assume, astronauts will read an object into the barcode system before placing it in a specified storage location. This will involve sorting through the objects and placing them somewhere. An RFID system would eliminate the need to read the object into a system, but it would not get rid of the sorting task. Further, astronauts would probably scan an object with the barcode reader after having selected it, but before storing it. Second, the design of an RFID gate will of course be very different at a future base. The important variable in our experiment with respect to gate-design, then, is not the exact configuration, but rather the kind of tags, the amount of RF power in the area, and the distance of the antenna's. In our case, each antenna produced one watt of power at 915 MHz. While the exact system configuration will of course be different on a planetary base, these studies will hopefully give some realism to assumptions made about their design. Third, it should be noted, contrary to an actual exploration situation, participants were in no way trained to use the tracking systems. For this reason, the results of the experiment may also include some "learning effect" as the process of sorting and recording the objects was better understood. This may have had a particularly important affect on the barcode part of the experiment, which necessitated understanding how to find and read each barcode.

5.4.2 Inter-Module Transfer Results and Discussion

The goal of this experiment was to let a tracking system run continuously and get an idea of the level of traffic at a given point. Figure 5.14 shows an example of the personnel tracking results.

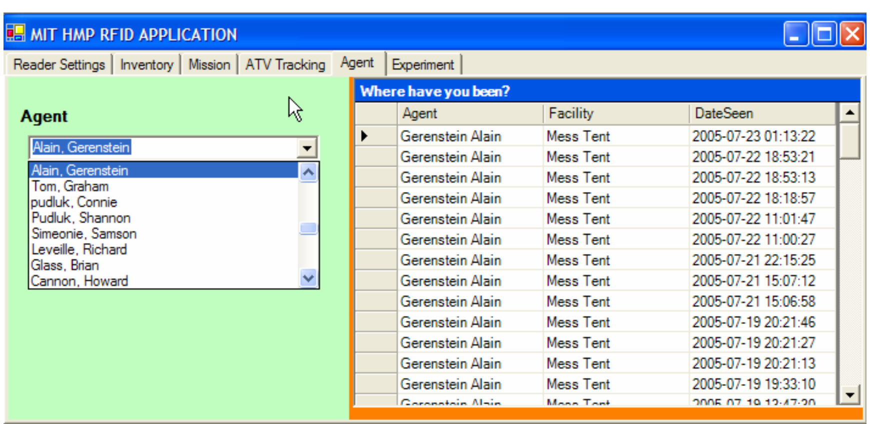
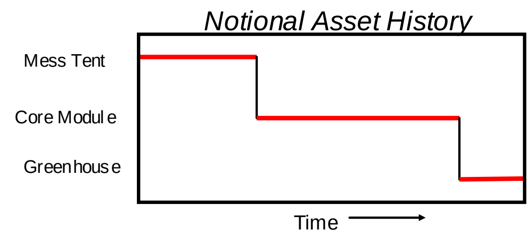


Figure 5.14: Inter-Module Human Tracking Application[35]

[35] "Gerenstein" (typo in database) in this figure refers to Alain Berinstain.

Figure 5.15 provides a summary of the data retrieved during the experiment's operation, including a "notional asset history" as an example of what such a system could eventually provide. The upper-right corner of the figure displays an example of the data retrieved. No logic was implemented on this data yet—as in the ATV experiment—so it only conveys when a person was near an antenna, and not whether they were entering or leaving the tent. Theoretically, this data could be used in any number of ways. The two graphs at the bottom of Figure 5.15 are recorded RFID read activity histograms.

Name	Date	Time
Thater, Hans	7/15/2005	15:19:21
Thater, Hans	7/15/2005	16:08:17
Thater, Hans	7/15/2005	16:08:57
Thater, Hans	7/15/2005	16:18:49
Thater, Hans	7/15/2005	16:26:58



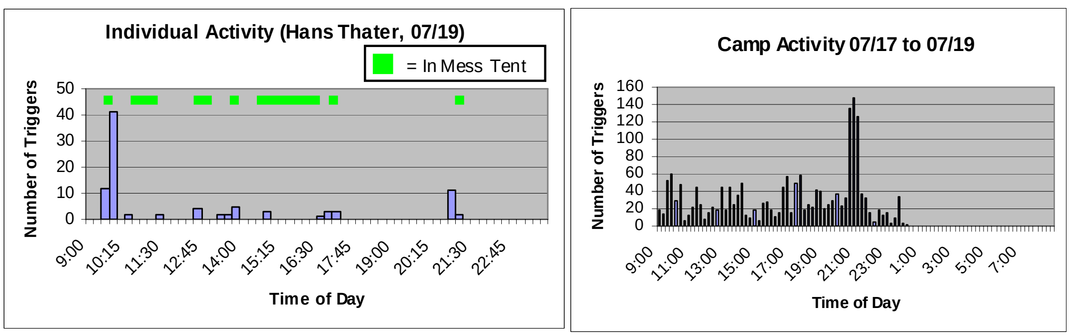


Figure 5.15: Summary of (Mess-tent) inter-module gate experiment

The graph on the bottom left is a histogram of the activity of one specific HMP participant during one day, partitioned into 15 minute bins. It illustrates how many "counts" the antenna read from a specific tag in a given 15 minute period. It illustrates a spike of activity around 9:30am, in addition to activity around lunch and dinner. The green lines above this activity are notional logic-based conclusions from the counts. They show how the data could be used to infer when a participant or asset was entering or leaving a given area. Without additional information, however, such logic would be dependent on 100% read accuracy. As discussed below, it is not clear that such an implementation would be reliable at this time, given other issues that arose with the previous experiment.

The graph on the bottom right of Figure 5.15 shows the total number of counts recorded by an antenna at a particular location, also partitioned into 15 minute bins. If the assets were tools or items other than people, this kind of information could be used to better understand usage patterns on the exploration base, such as where an asset is most often moved/used. In this case, it

demonstrates a clear increase in activity after dinner time, around 9pm, with relatively constant activity during the day and no activity at night[36].

More than the data collected, the most useful part of the Mess-tent experiment involved understanding how the system, people, and tags, interacted and how this might inform future design. Our observations in this regard can be divided into three basic categories: HMP specific, non-HMP specific, and technology-related.

1. HMP specific observations had to do with environmental issues at HMP itself, and are therefore less relevant to future exploration missions. Most significantly, the location of the antenna's caused some problems because it interfered with camp activity. We wanted to monitor traffic in and out of the Mess tent because this was the one area where everyone passed through at one time or another. However, either side of the mess tent entrance was filled with coats, chairs, a wooden shelf with shotguns, ATV helmets, and radio communications gear and other items. Further, this location became exceedingly dirty and was often quite moist due to the rain. These environmental factors undoubtedly affected the data, and also made the system difficult to manage. It would have been better to integrate the RFID antennas seamlessly into the existing infrastructure.

2. Non-HMP issues include software and hardware issues. Most importantly, as the formal experiment demonstrated, passive tags are not 100% accurate at this distance. The goal for such a system would be to track assets as they move from module to module. In the absence of 100% accuracy, redundancy or other methods would need to be implemented to guarantee tracking. This might include location sensing, or setting up multiple antennas along a corridor to track movement. It may be sufficient, to create specific RFID sites, rather than create a base-wide tracking system.

3. Finally, the tags themselves were not extremely sturdy. We used standard passive tags provided by Alien Technology. When people put these in their pockets they often became bent or simply did not work due to interaction of the human body with RF waves (the high water content of the human body absorbs RF waves). This issue, however, could be easily overcome by designing RFID compatible cases for the tags and/or identifying better locations for them. This should be addressed in a future expedition to HMP to design a more comprehensive tracking system.

5.4.3 ATV Tracking Results and Discussion

The ATV experiment was essentially a technology demonstration for the battery activated passive tags and the potential to create a stand-alone system to regulate traffic in and out of camp. Figure 5.16 illustrates a snapshot of our raw results for the experiment.

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[36] It never gets dark at HMP during a summer campaign as the site is north of the Arctic Circle and the sun never sets below the horizon during this time of the year. Nevertheless, researchers at HMP attempt to follow regular sleep patterns to maintain their productivity and health.

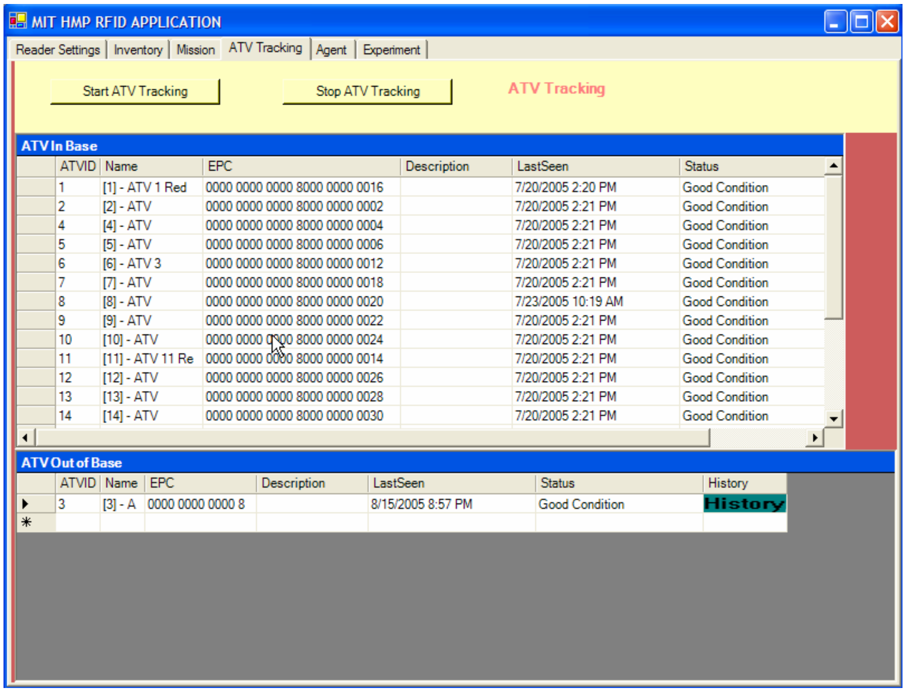

Figure 5.16: Snapshot of ATV tracking raw results

The data generated proved the basic concept but again was not 100% accurate. If an ATV passage event was missed at any time during the day, the program (part of layer 2, Fig. 5.4) would thereafter attribute an entrance to an exit or vice-versa. Table 5.2 shows a snapshot of the reduced data. Further, as noted above, it turned out that one of the antennas used did not work, resulting in a reduced read probability.

Table 5.2: ATV Data

ATVID	Date Left Base	Time Left Base	Date Return Base	Time Return Base
1	7/26/2005	12:47:31	NULL	NULL
1	7/28/2005	23:11:35	7/29/2005	1:27:56
1	7/30/2005	14:28:24	7/30/2005	17:01:03

Still, some conclusions can be drawn from the experiment and basic results used for developing future systems. From a hardware perspective, it is clear that the battery-activated tags do not appear to have the 30 meter range claimed for them by the manufacturer's specifications. This suggests that, for HMP at least, future long-range applications (such as ATV tracking) should use active tags rather than battery-activated passive tags.

Active tags would radiate with more power than battery activated passive tags, making the need to avoid RF interference even more acute. As noted, we implemented the ATV tracking system well outside of camp to avoid RF interference. This worked well, and the 5.6 GHz relay antenna was reliable. However, a basic goal should be to reduce RF interference, mass and complexity

where possible, so future experiments using high-frequency radiation would be better off addressing the problem in less complicated ways.

These issues notwithstanding, the basic tracking data is useful and can have applications beyond real-time asset management. Figure 5.17, for example, uses the tracking data to estimate total usage rates for each individual vehicle. It demonstrates that some vehicles were used much more than others over the three-day period. This information could be fed back to base managers to optimize usage and minimize repair needs.

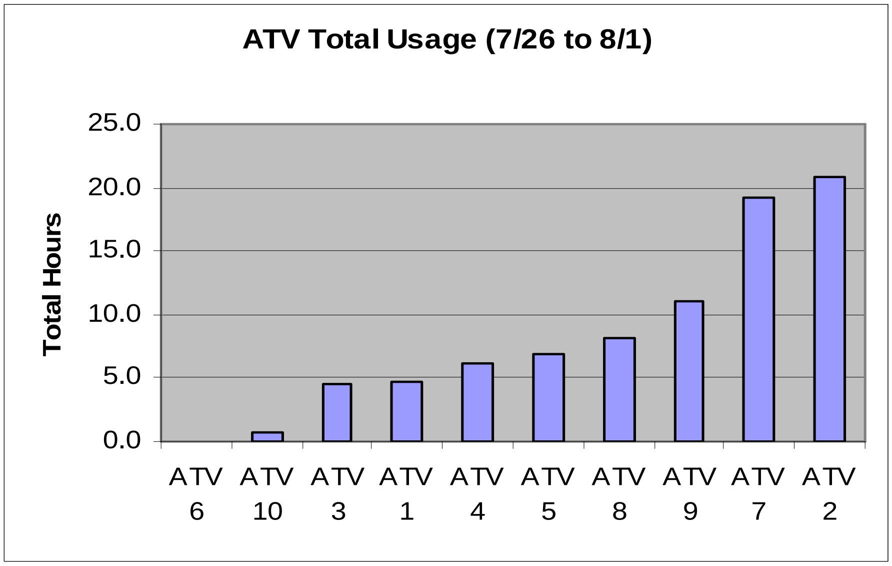

Figure 5.17: Sorted ATV usage rates based on RFID tracking

5.5 RFID Conclusions and Recommendations

The basic ability to associate an object with information and then to autonomously track the location and state of assets, agents and vehicles, has the potential to help many aspects of surface operations. Most obviously, it could save researchers precious time by accurately and effortlessly tracking objects as they move about base, and reporting exact levels of supply. It could also enable more exotic applications, such as the rapid “check-out” of a vehicle for traverse using hand-held readers; by creating “smart shelves” that sense what items are on them, it could also save researchers precious time locating and analyzing rock and soil samples that are obtained during field excursions.

Our results suggest that while RFID technology will undoubtedly save time, basic improvements in accuracy and system design will be needed to justify their cost and mass. Most likely, special packaging would be needed to overcome basic problems of radio-wave reflection and attenuation. This is especially true for metallic containers and items containing fluids. Further, it became clear that to avoid RF interference an RFID system needs to be designed together with the overall communications architecture of the base, rather than retrofitted as an afterthought.

Perhaps more importantly, our experience at HMP has revealed more issues and questions that need to be addressed before a comprehensive RFID solution for space and planetary exploration can be created:

Issues:

- Products with metal packaging will reflect radio waves in unreadable ways.
- Water and products with high water content absorb radio waves, reducing read range.
- Readers can interfere with existing wireless equipment in a transport vehicle or habitat.
- Motors emit electromagnetic interference, interfering with readers.
- Radio waves are often not focused in the desired area.
- The read distance and field of view (FOV) should be tailored to a particular location.

Questions:

- What amount and type of data will be stored?
- Must data be updated?
- Will tags be moving, how fast and in what orientation?
- What are limits on tag size, shape, and orientation?
- Will tags be disposable or reused?
- Will tags be operating in cold, wet, dirty, hot, muddy, dusty environments?

Answering these questions will help us design better systems, both for testing at HMP, and for potential in-space applications. These issues and questions were raised in the course of our field research at HMP and would likely not have come up to the same extent in a climate controlled, pristine RFID laboratory facility. We found that HMP is an ideal, albeit challenging, environment for agent and asset tracking research because it:

- represents a “semi-closed” environment similar to a lunar or Martian research station
- features a rich, yet manageable set of agents (people), supply items and vehicles to track and analyze
- is subjected to varying temperature, dust and weather conditions that stress equipment, often to the breaking point
- provides for natural usage patterns of equipment, vehicles, consumables and people movements in the context of an analog planetary exploration base.

We will continue to refine the experiments conducted at HMP and will pursue further development of agent and asset tracking technologies in the future based on these initial results.

6 EVA Logistics

In Section 4 we distinguished between macro-logistics and micro-logistics for planetary exploration. The network in Figure 4.1 illustrated that one of the main concerns of exploration logistics is the transportation of crew and cargo from supply nodes to planetary surface nodes, such as a research station like HMP or a lunar or Martian base. This movement of crew and cargo across large distances (> 100 km) is what we call macro-logistics.

In the previous section we described our research in tracking agents and assets while at the research station itself. Concerns about the movement of items and people from one module to another and around the immediate vicinity of the base (typically within a radius of 100-200 meters) begin to address on of the aspects of micro-logistics. The true value of an exploration infrastructure, however, manifests itself through its ability to support short (< 1 day) and long (> 1 day) excursions away from base. It is during these activities that exploration and science data and sample gathering (e.g. for planetary geology) take place. This section therefore discusses initial work done on micro-logistics away from the HMP RS. We refer to these micro-logistical activities collectively as Extravehicular Activity (EVA) logistics.

6.1 Macro- versus Micro Logistics

Macro-logistics refers to the global capacity to support EVA. From the point of view of an expedition on a planetary surface, this would encompass elements such as:

-number and characteristics of space suits
-number and type of surface vehicles
-airlock characteristics
-suite of EVA tools
-capability to use planetary resources during EVA (ISRU)

In short, the macro-logistical capability of an expedition is determined back on Earth during the planning phase. Once an expedition is on a planetary surface, macro-logistical capability can change by the breakage or deterioration of equipment or by the arrival of resupply missions.

Micro-logistics, on the other hand, involves the planning of each individual EVA. Micro-logistical planning must be conducted within the envelope of the expedition's macro-logistical capability. Planning for each EVA must consider the goals of the EVA, which will in turn determine the distance to be traveled, duration, and tool and consumable requirements. Path planning, which we studied extensively, is a critical part of EVA micro-logistics.

The biggest difference between conducting planetary surface EVAs and simulated EVAs at an analog site like the HMP RS is, of course, in the life support system requirements. These can be simulated in exercises like "Desert Rats", but we did not attempt this at HMP. On the other hand, the selection and use of different vehicles at the HMP RS has many similarities with surface mobility operations on the Moon or Mars.

Our EVA-related studies at HMP in 2005 concentrated on micro-logistical problems, which are described in the following sections.

6.2 EVA Observation Research Methodology

From an operational point of view, HMP provides a unique opportunity for scientists and engineers to acquire *experience* in dealing with many of the factors that are associated with human planetary space exploration extravehicular activities. These factors include finite resources, remoteness, limited communications, operations in spacesuits (simulated by wearing prototype spacesuits during excursions), and the implementation of new technologies (under simulated Martian conditions). For this reason, excursions at the HMP RS provide insight into how future explorers may go about planning and exercising en-route re-planning during planetary surface excursions. We observed and participated in a number of HMP excursions, in order to delineate the set of parameters that are likely to drive EVA micro-logistics requirements.

We documented eight different HMP excursions (or traversals) during the course of the 2005 season. Because of the diverse group of researchers participating in the HMP, we were able to observe a variety of different types of excursions. For example, Hamilton Sundstrand, manufacturer of the current space suits for Space Shuttle and International Space Station, sent a team to HMP this past summer to test their Concept Spacesuit for Advanced Planetary Exploration (see Appendix I for selected pictures). Science-driven excursions ranged from including only two scientists on foot, to up to nine participants using All Terrain Vehicles (ATVs).

Excursions were documented in a standardized manner, to the extent possible, using an EVA-log (see Appendix G) created to capture planning and re-planning, as well as events triggering re-planning. Using the EVA-log, we documented each excursion through a combination of: observation of pre-excursion planning session and post-excursion debriefings, pre- and post-excursion interviews with the excursion lead and other excursion participants, and observations from our own participation in the excursion. We used a combination of these methods unique to each situation in order to best capture as many excursion experiences as possible, and without interfering with preparation for and execution of the excursion.

Three excursions each were documented through observing the pre-excursion planning and debriefing sessions, and conducting interviews. This combination of methods was the most time efficient in terms of capturing the key planning and re-planning issues encountered in an excursion. Two excursions were documented through the observation of pre-excursion planning sessions and participation in the excursion. This combination of methods, although time intensive, was the most informative, allowing us to identify metrics that had not been considered in our research prior to the HMP season.

Observations of planning sessions and pre-excursions interviews were recorded in the EVA-log. During the debrief session, the traverse leader for the excursion often reviewed the original plan recorded in the EVA-log, and pointed out unexpected deviations from the initial plan. We recorded these deviations for the excursions that we participated in. This exercise revealed the

circumstances under which traversals must be re-planned and how the people in the excursion adapted to these changes. The observation of EVA traverses also included an inventory of items taken along. These items generally fell into the following three categories:

- consumables: water, snacks, …
- safety: medical supplies, radios, Iridium satellite telephones, shotguns
- research: binoculars, notebooks, cameras, sample bags, geology tools, ...

These were in addition to the obvious requirements of:

- mobility: ATV's, navigation equipment (maps, GPS),…
- personal clothing: hats, rain jackets, goggles, …

Aside from the "EVA Log" (Appendix G), other forms of excursion documentation included digital audio recordings and extensive notes taken during planning meetings, interviews, and debrief sessions. When possible, digital imagery was used to also characterize the excursion. A hand-held GPS receiver was used to track the traversed path and indicate waypoints for a few of the observed excursions[37]. We achieved only limited success with this method since it was not applied systematically to each excursion.

In summary, a variety of excursions were documented in the "EVA Log" through observation of planning and debrief sessions and interviews of researchers at HMP. Other forms of documentation included recordings of excursion-planning sessions, interviews, and GPS-tracking of excursion routes. Full documentation of the EVAs can be made available upon request.

6.3 Results/observations of 8 EVAs at the Haughton-Mars Research Station

After observing and participating in a number of HMP excursions, all the information was distilled, resulting in a set of parameters that are likely to drive EVA micro-logistics requirements. Below, one observed HMP excursion is described in detail in order to illustrate a typical excursion and the manner in which these were reviewed and assessed.

Example of Observed HMP Excursion

- Goal of Excursion: The objectives of this excursion included taking gravity measurements, collecting soil samples, and conducting gully surveys at several different sites within Haughton Crater. The objectives of this excursion form a part of a longitudinal study to observe changes in the land over time. Much of Haughton Crater is Inuit-owned land and as a result permission is required to enter this area. This was one of the few opportunities in the 2005 season that the researchers had to traverse this area and achieve their objectives.
- Number of people: Four people participated in this excursion: one conducting the gravity measurements, one for soil sampling, and one for gully surveying (one for each objective). The fourth member of the excursion served as a security officer.

[37] Automatic GPS traces of actual traverses were not recorded, but could be included in future years.

- Number of sites to be visited: The participants initially planned to visit six sites using the all-terrain vehicles (ATV) available at the HMP RS. The sites are summarized in Table 6.1.

Table 6.1: Overview of 6 target sites for Haughton Crater EVA (HMP 2005)

Site	Tasks	Est. True Dist.	Est. Path Dist	Est. travel time	Mobility
Junction	Gravity measurement	5 km	7-8km	20-30 min	ATV
Tripod Hill	Gully system photography, & gravity measurement	5 km	7-8km	20 min	ATV
Old Base Camp	Soil sample	3km	4km	15 min	ATV
Anomaly Hill	Gravity measurement	5km	7-8km	30 min	ATV
Perseverance Hill	Gravity measurement	<1 km	<1km	5 min	ATV
Base Camp	Gravity measurement	10 km	13-14 km	35 min	ATV

- Estimated total time: The traverse leader estimated that it would take a total of 4 to 5 hours to complete the excursion. This time was calculated based on the number of sites, the estimated time it would take to reach each, and the estimated time spent at each site. This traversal was also unusual in that it had a real time pressure element; two of the three researchers were scheduled to leave that evening on an airplane out of Devon Island – and they could not delay nor extend their stay at camp. Most excursions did not have this time pressure as there was no real cost involved with returning late to camp.

- EVA Inventory:
    - Excursion Supplies:
        - Some water (~ 1 liter)
        - Lunch (power bars and other snacks).
        - Rubber boots
    - Critical Supplies:
        - Ropes to free ATVs stuck in mud
        - Tire pump
        - 2 safety radios
        - Small first aid kit (only need a small kit, because of infrastructure (base camp, radio, airlift) that is in place in case of an emergency
        - Shotgun (loaded)
        - Tarp

- Scientific Equipment:
    - 2 Cameras
    - GPS handheld
    - Gravimeter, backpack, tripod
    - Sample tools: scoop, containers, water to rinse
    - Plastic sample bags for rock samples
    - Rock hammer

- Planning: One designated traverse leader led the planning meeting. He gathered the information needed from each of the other participants. They used maps, both topographic and aerial, and verbally described the sites, the objectives and the path they would take to accomplish the goals of the excursion. They talked through a safety checklist, verifying that they had the appropriate ATV, radios, and shotgun. All three researchers involved in the excursion were already familiar with the area and the terrain they would encounter. Most of the discussion centered on finalizing the number of sites they were going to visit and, because of the time pressure, a prioritization of sites.

- Environmental factors affecting excursion: The group anticipated a few locations along the path that would be difficult to traverse, due to wet weather over the previous couple of weeks. Since they had not yet been into the crater during the 2005 season, they did not know the condition of these areas. However, years of exploring had taught them that certain spots were traditionally difficult to navigate with the ATVs.

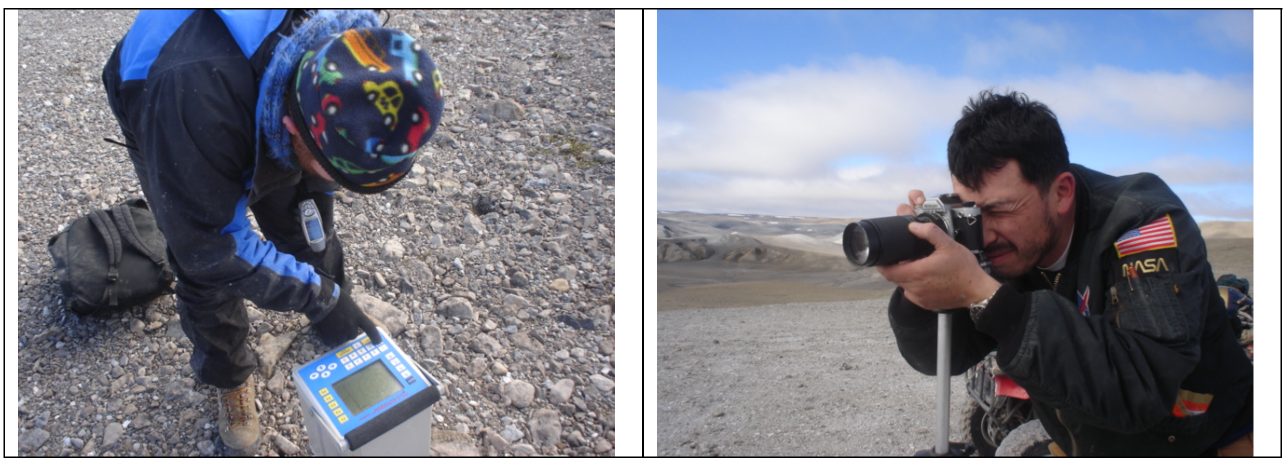

Figure 6.1: Researcher taking gravity measurements (left); researcher taking photographs of gullies (right)

- Post-EVA debrief: After the excursion, the traverse leader discussed event triggering re-planning. The path the researchers chose had been very difficult to drive; the ground bearing strength of certain areas was decreased due to muddy conditions. The ATVs got stuck several times in locations where they had not expected difficulties. This delayed the excursion schedule. Furthermore, the participants in the excursion were unable to

reach one of the key sites, Old Base Camp[38], because the conditions of the ground were impassable for the ATVs. The researchers re-planned; they considered walking to the site but deemed it not feasible due to time constraints. They then attempted to reach the Old Base Camp via another route. Partway through this leg of the traverse, they realized the terrain along this re-planned path was also impassable. Eventually, the excursion participants decided to remove the Old Base Camp site from their list of sites to visit and instead focus on accomplishing the goals at the other remaining sites. This was not an easy decision since the Old Base Camp was the only site of interest to collect soil samples. Later in the excursion, the participants were not able to reach the latter sites on ATVs, and had to walk to Perseverance Hill from Anomaly Hill. They all eventually returned to camp, just in time to catch the plane leaving Devon Island. Their total time spent on the excursion was about six hours.

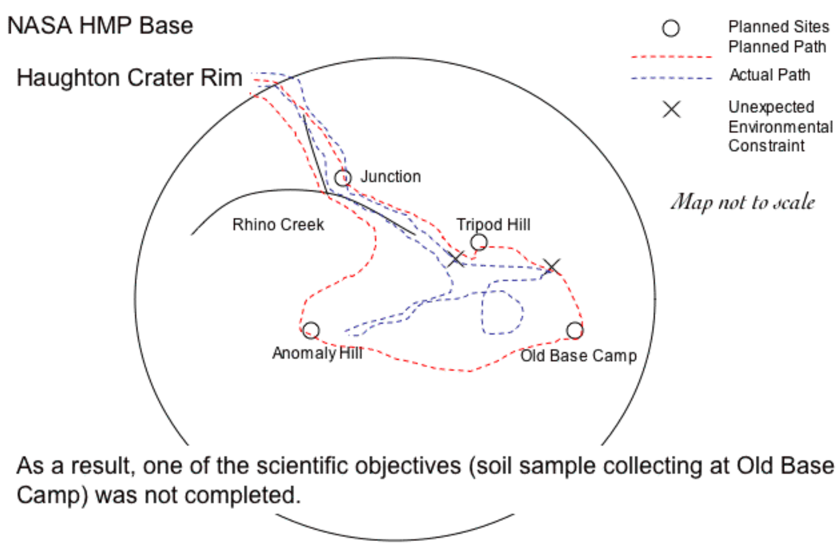

Figure 6.2: Haughton Crater excursion sketch, planned vs. actual

6.3.1 Preliminary Surface EVA Parameters

All the HMP excursion "EVA Logs", the interviews, and observations were assessed and distilled into a preliminary list of planetary EVA parameters that characterize excursions and the information necessary to delineate the set of parameters that are likely to drive EVA micro-logistics requirements (see Table 6.2).

Table 6.2: Preliminary Planetary Surface EVA Parameters

Parameters	Information
Goals of excursion	• Objectives • Priorities of objectives
Estimated total time	• Safety/contingency margin

[38] The old HMP base camp site inside the Haughton Crater had been used during the early years, approximately 1997-1999, but was subsequently moved to the crater rim where the current base is located.

People on excursion	• Number of (quantity)
	• Role and individual objective
	• Experience (correlates to mobility's speed)
	• Type (& identification) of supplies carried
	  o Safety critical equipment
	  o Scientific equipment
	  o Excursion equipment
	• Effects of large group

Sites to be visited	• Number of (quantity)
	• Location
	• Path taken
	  o Absolute distance & path distance to/between sites
	  o Time to travel to/between sites
	• Time required at each site

Mobility used	• Type of mobility (envelope of vehicle capabilities) • Traverse speed (maximum, minimum, average) as a function of terrain • Energy consumption rate as a function of terrain
Terrain characteristics	• Elevation, slope • Photographic view, aerial and from ground point of view • Trafficability (rock density & size, ground bearing strength) o Relationships with type of mobility • Pre-determined paths, areas of difficulty, landmarks, preferred waypoints • Explored/unexplored area (correlates time spent way-finding)
Environmental characteristics	• Weather conditions (pertinent to Earth and Mars) • Glare, sun position (pertinent to Earth, Moon and Mars)

6.3.2 Constraints on Surface EVA

Once parameters that are likely to drive EVA micro-logistics have been delineated, the next step is to identify the constraints on these parameters. While the identification of these constraints is informed by our observations at HMP, it is worth noting that the sets of constraints observed at HMP are difficult to generalize to future Moon or Mars excursions. Excursions at HMP are not usually constrained by time limitations, whereas EVAs on the Moon or Mars will have time constraints imposed, primarily by EVA life support limits

We assessed the applicability of all HMP constraints to planetary space exploration. For example, safety concerns significantly impact planning at HMP. Every excursion group had to carry at least two radios and a shot gun (to protect against possible polar bear attacks). There is no "shot gun" analogy in human space exploration, yet an important constraint for surface EVAs will be the satisfaction of safety requirements; astronauts may be required to take spacesuit repair kits instead, for example, as well as carry beyond-the-horizon communications gear. A preliminary list of constraints for surface EVA, derived from observations at HMP, is shown in Table 6.3.

Table 6.3: Preliminary Constraints on Surface EVA

Constraint	Information
Communication constraints	• Communication system set up o Line of site o Maximum distance from beacon • Minimum number of radios (handheld or built-in)
Type of mobility constraints	• Maximum consumable energy or fuel (power, range) • Maximum time of use • Terrain traversable (includes max/min slope, rock density & size, ground bearing strength) • Visibility • Reliability of system (rover & spacesuit)
Safety constraints	• "Walk-back" requirements (e.g., access to re-supplies, caches, bringing back crew to home base) • Redundancy (e.g., radios, rover) • Emergency supplies requirements • Overall margins on fuel and life support • Inoperable environmental conditions • Required excursion group composition based on mission

6.3.3 Defining Planetary Extra-Vehicular Activities: Parameters and Constraints Flow

Before developing EVA micro-logistics requirements, one must first precisely define all the variables that define planetary EVAs. Once the parameters and constraints are delineated, these can be arranged into a flow diagram to show the relationships between them for planetary EVA (Figure 6.3).

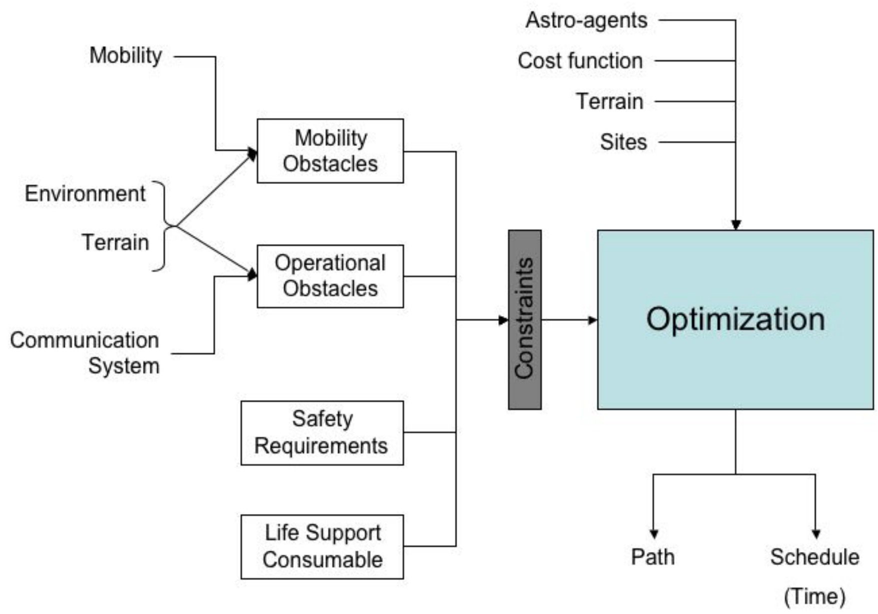

Figure 6.3: Planetary EVA, parameters and constraints

The minimum (generalized) parameters that define a planetary EVA are a path and a schedule (time). Each parameter and constraint is further subdivided into more precise information (details of these can be found in Appendix H: Details of Planetary EVA Parameters and Constraints). For example, the parameter "*Path*" includes more than just the path segments between sites, but also the energy consumed along that path. We have also identified a set of minimal input parameters that need to be specified for every planetary EVA; these are sites, terrain, cost functions, and astro-agents (astronauts or robotic explorers). "*Sites*" refers to not just the number of them and their location, but also their priority, what needs (tasks) to be accomplished at each site, how long each task is expected to take, how much energy is consumed doing the task, and the mass of equipment needed to accomplish the task. We have essentially taken the list generated before and mapped it to a generalized flow diagram, and further expanded on each parameter and constraint, enumerating the information each should contain.

6.3.4 Lessons Learned about Planning and Re-planning Excursions

Traverse leaders of excursions were often long-time participants of HMP (some dating back to its inception in 1997), and played a crucial role in the planning and execution of excursions. The traverse leader organized the planning meetings, reviewed objectives to be accomplished, suggested a path and waypoints, gathered input from the rest of the excursion group, and ensured that all the safety precautions were met. They used both topographic and aerial maps of the area to plan the route. This same leader was first in line during the traverse; they determined the real path, scouting and testing sections of the route for passability. Typically, the excursion leaders were responsible for the group as a whole and making sure no one was left behind. Certain areas were very muddy, and occasionally, ATVs would be rendered immobile if they sank too deep. The traverse leader provided the leadership to extract the ATVs, since they had dealt with similar circumstances before. Experience with such situations will be vital for safe and effective Moon and Mars exploration as well.

Traverse leaders draw from their wide range of experiences over the years to form many mental models for accomplishing the task of planning and re-planning traversals. One of the most useful mental models to traverse leaders was an understanding the feasibility of traversing different routes. They knew where problem areas were and knew how to avoid them. They were also able to fairly accurately estimate total times and path distances. This included estimating the time spent at sites using a mental checklist of the activities required to accomplish the objectives. The traverse leaders exhibited fairly well developed survey knowledge of the area, i.e., a good sense of where they were. They understood the speed and terrain limitations of the ATVs.

However, the traverse leaders' mental models were not always correct. For example, traverse leaders typically underestimated the predicted total times for the excursions. Occasionally, traverse leaders experienced a lapse in their survey knowledge of an area. For example, one traverse leader did not remember what parts of a valley could be reached by ATV. In another instance during an excursion, a traverse leader spent time attempting to follow an alternate route that turned out to be impassable. The lack of an aerial map available in real-time prevented the excursion participants from re-planning a successful route.

Several of these mental models cannot be fully automated in future planning and re-planning decision support tools. However, we can increase the validity of these mental models by providing information support. For example, we can display a complete set of pre-determined routes and model the trafficability of the terrain based on its currently known conditions, correlated against the ATV's (rovers, in the case of space exploration) capabilities. Other possibilities for information support are identified in Table 6.2.

6.4 Future Work

The parameters and constraints delineated from the HMP excursion observations constitute the initial step in identifying precisely what a planetary EVA is, and furthermore, to define micro-logistics requirements. Since the model is based of HMP observations, and though the original assessment included a space exploration perspective, the model may be biased to Earth-based exploration. Thus, the next step is for this preliminary model to be peer-reviewed by colleagues within the field of human space exploration in order to identify any missing information that pertains specifically to Moon and Mars human and robotic exploration. Additional comments about future work in this area are given in Section 7.5.

7 Conclusions and Recommendations

7.1 Key Results and Observations from HMP 2005

7.1.1 Classes of Supply

As far as manned space flight goes, there are no standardized supply classes used by NASA across different programs (e.g. Space Shuttle, ISS). Each program has developed their own categories used in manifest planning, cargo planning, and stowage planning. The categories match up with organizational structures and are different in each program. Since the operational requirements are different in the Space Shuttle Program and the International Space Station Program, integration has been problematic, resource planning has suffered, and the organizational structure has actually grown in both programs to cover communication between programs.

In anticipation of future space logistics requirements, we have developed a generic classes-of-supply (COS) system, organized around the key functions (processes) that need to be accomplished in conjunction with human-robotic planetary and space exploration. An object-process map (Fig. 3.1) was developed, resulting in the following 10 classes of supply:

Table 7.1: Class of Supply (COS) for Exploration Logistics

1.	Propellants and Fuels
2.	Crew Provisions
3.	Crew Operations
4.	Maintenance and Upkeep
5.	Stowage and Restraint
6.	Exploration and Research
7.	Waste Disposal
8.	Habitation and Infrastructure
9.	Transportation and Carriers
10.	Miscellaneous

This system of classification was validated in two ways. First, we cross-correlated the COS against the current Cargo Category Allocation Rates Table (CCART) used on the International Space Station (ISS), see Table B.5. We were able to assign all 14 major CCART categories to the proposed 10-class-of-supply system. Second, we validated the COS by conducting a detailed inventory of items at the HMP Research Station during the 2005 summer field season. This enabled us to create a total of 44 sub-classes of supply (Table B.6).

7.1.2 Current HMP Inventory

We conducted a detailed inventory of a total of 2300 supply items at the HMP Research Station. In order to do this systematically, we had to first develop standardized procedures for recording the inventory (see Section 3.2). This consisted of first defining a list of supply item attributes as a

building block for a relational database. A total of 50 attributes were defined to capture the status of HMP supply items on base (see Figure 3.18). These are broken down into generic supply class attributes (6), supply type attributes (24) that are common to all supply items, supply item attributes (12) that apply only to particular instances of supply items, as well as an item history (8) that records the past history (such as location and operational status) of particular supply items. We were not able to record all attributes for all supply items at HMP 2005, but are confident that we have created both the procedures and technology to do so in the future. We believe that this database structure needs further development, but its current state represents an excellent starting point for future planetary exploration logistics.

Of the 2300 items recorded at HMP we have transferred 1900 from initial Excel spreadsheets (Fig. 3.2) into a relational SQL Server 2000 database (Fig. 3.17). The beauty of this database is that it can easily generate reports that are tailored to various users in the exploration enterprise (see Appendix E): astronauts, mission operators, load masters, vendors/procurers and logistics modelers, while always reading and manipulating the same core data. We believe that this will significantly alleviate problems with currently fragmented, hierarchical databases that are incompatible between various national and international organizations. We will make the HMP 2005 relational database available to HMP project participants on a password-protected website for future use.

Using this capability, we have analyzed the HMP inventory according to various criteria. Of the 2300 supply items, 23% are food related items (COS 2.2), 15% represent communications equipment (COS 3.5), 11% are categorized as scientific instruments and technology research equipment (COS 6.1) and 9% of the items pertain to health care equipment and medical consumables (COS 3.3). A complete breakdown of the HMP inventory by COS is shown in Figure 3.3.

A somewhat different picture presents itself when the HMP inventory is analyzed in terms of its mass breakdown (Fig. 3.4). In all we recorded items with an approximate total mass of 20,717 kg (= 45,580 lbs) at HMP (Table C.1). It should be noted, however, that this does not include the mass of the already erected structures (e.g. the Mess-tent, Arthur C. Clarke Greenhouse …), which we estimate will add at least 7 metric tons to the actual inventory. Thus, a lower bound estimate of the man-made, imported materials present at the HMP site is 27.7 metric tons. A mass breakdown of the 20.7 tons that were recorded, reveals that nearly half (46%) is made up by the transportation vehicles (Humvee, ATV fleet). Other items included, in order, various fuels and propellants (20%), crew provisions (14%), exploration and scientific research equipment (8%) and various equipment and subsystems for habitation (e.g. heaters) at 5% of total mass. In Section 3.3 we compared this mass breakdown in detail by sub-class of supply in terms of its analogy to a lunar exploration base. A summary of our conclusions in terms of HMP's analogy with space (planetary) exploration logistics is provided below (Section 7.2).

In totality our actual HMP inventory yielded a mass of 20,717 kg, versus 23,740 kg for the pre-HMP estimate (Table D.1). This is a *15% difference* and is suggestive of the level of precision of our current planetary logistics requirements modeling capabilities. However, this conclusion might be somewhat premature as some items have not yet been included in the HMP inventory (e.g. tents) and we suspect that the *actual inventory mass at HMP is closer to 25-30 metric tons*.

Still, with short term lunar mission requirements (Apollo-style) estimated at 10,082 kg and long lunar mission logistics requirements estimated at 36,529 kg we see that HMP falls right in the middle between the two (see Appendix D). Some aspects of HMP, such as short individual stays of 12 days on average, are more like the short-term Apollo-style missions, while other aspects, such as the semi-permanent research infrastructure, are more like the proposed 180-day lunar missions.

7.1.3 HMP Crew and Cargo Flows (Network Model)

The starting point of any logistics analysis is to understand the locations (=nodes) of any facilities (e.g. warehouses) and their interconnections in the larger transportation system. We have therefore modeled the HMP logistics system as a supply chain network (Fig. 4.1) and found that route 1-3-5, Ottawa-Resolute-HMP, must be considered as the critical path in that network, despite the existence of alternate transportation routes. The capacity on these routes depends primarily on the number of flights that one is willing to allocate.

For the critical arc between Resolute (node 3) and the HMP RS (node 5), we recorded a total number of 28 Twin Otter flights and one helicopter flight for the 2005 HMP field season (Appendix F). These flights can each carry between 2400-2800 lbs of payload for the 45 minute flight from Resolute to the HMP RS and are estimated to have carried a cumulative amount of 50,550 lbs (= 22,750 kg) into HMP during the field season. This represents an average load of 1740 lbs per Twin Otter flight, corresponding to an average 73% capacity utilization (inbound). The total outflow of cargo from HMP to Resolute was estimated at 27,630 lbs (=12,430 kg). This represents an average outbound load of 950 lbs, representing an average outbound capacity utilization of 40%. The net gain of mass at HMP during the 2005 field season is estimated to be 22,920 lbs (= 10,320 kg). This number is probably somewhat too high, because we tracked inbound cargo more carefully than outbound cargo. Nevertheless, the overall conclusion is that more material was brought to HMP than was removed from it. This is clearly true, as 2005 was characterized by substantial construction activity (three new tents/modules were erected, see Fig. 2.3). We also suspect that a number of teams bring more equipment than they remove, because they intend to reuse equipment in future years

The duration of the HMP field season for this year (2005) was 29 days. A total of 56 people participated in the HMP campaign, amounting to 683 crew days. The average time which a person spent at the HMP RS was 12.2 days. Rather than being a smooth “boxcar” distribution, the distribution of researchers and support personnel at HMP over time resembles a triangular distribution (Fig. 4.4). This causes two main problems. First, Twin Otter flights are used asymmetrically (see Table 4.3, and Fig. 4.3) with flights from Resolute to HMP in the first half of the field season being mainly full on the inbound leg and mainly empty on the outbound leg, with the reverse being true in the second half of the field season. Secondly, this distribution can cause congestion at the HMP RS during peak times and can be a driving factor for logistics requirements (sizing of food preparation equipment, waste disposal…).

The total estimated mass flow associated with the 56 personnel flown in and out of HMP (assuming 300 lbs per person) is 16,800 lbs. This accounts for the body mass of individuals, full clothing and personal gear, including individual tents. We assume that all personal gear is

removed from HMP and, thankfully, no individuals were lost. The conclusion is that 33%, i.e. exactly one third of the inbound cargo flow is due to individual researchers, whereas two thirds are due to construction equipment, vehicles, spares, food and other consumables as well as scientific equipment. Of the outbound cargo, personnel and their gear accounted for 61%, i.e. nearly two-thirds of the transported mass, whereby the remainder was due to scientific equipment, various waste, empty fuel containers and broken equipment (e.g. ATVs to be repaired) being returned.

Based on the difference between the actual number of flights that occurred, 29[39] versus 20, we estimate that the optimization potential for HMP transportation for the leg between Resolute and Devon Island may be on the order of 30-40%. This, however, would require more precise apriori knowledge of cargo masses and volumes, more careful staging and weighing at Resolute and the formal establishment of a reverse logistics staging area at the HMP airstrip, along with smoothing of the HMP participant schedule. Significant improvements in flight scheduling and manifesting are possible and desirable, and could lead to cost savings upwards of $25,000 for a single field season. It is important to acknowledge, however, that flexibility and robustness are at least as important for HMP transportation as optimality. We found that there are key uncertainties in Arctic air logistics that can render any detailed apriori flight plan obsolete:

- weather and soil conditions can change from one minute to the other
- other research stations and field parties are competing for the same airplanes
- airplanes can be unavailable due to technical problems
- cargo estimates in terms of mass and volume are imprecise, loads might have to be split up in ways that were not originally planned
- personal medical emergencies can arise and cause airplanes to be rerouted

Rather, what is needed is real-time awareness and optimal re-planning capability to adapt the flight schedule on a daily or even hourly basis (see Fig. 4.2).

7.1.4 RFID – Agent and Asset Tracking

One step in the direction of such a real-time logistics capability for planetary exploration was taken with the series of RFID experiments conducted at HMP. The basic ability to associate an object with information and then to autonomously track the location and state of assets, agents and vehicles, has the potential to help many aspects of surface operations. Most obviously, it could save researchers precious time by accurately and effortlessly tracking objects as they move about base, while also reporting exact levels of supply.

To assess the potential value, but also limitations of RFID in the context of planetary exploration, we first conducted a formal experiment around the concept of an “RFID Gate”. Such a gate was installed at the entrance of the MIT tent. We tested the hypothesis that automatically tracking the movement of supply items in and out of a module or habitat would be significantly faster than using traditional barcode readers, as is current practice on the International Space Station (ISS). We conducted a total of 120 runs, varying the technology used (RFID versus barcoding), the number of items tracked at once (10 vs. 20) as well as the configuration of the

[39] Excluding a separate helicopter flight.

RFID antennas (2 vs. 4). We found that RFID reduced the time to track items from above 140 seconds with barcode readers to below 50 seconds with RFID, thus a factor of 2-3 in time savings (Fig. 5.12) appears possible. Also, the standard deviation of time consumption was significantly higher with barcoding than with RFID, because the process depended more on individual factors such as familiarity with the technology and efficiency. On the downside, we found that the RFID system was only between 70-85% accurate, i.e. between 15-30% of all transactions were missed, whereas the barcoding system was 100% accurate (Fig. 5.13). We found that there are a number of critical factors that drive RFID system accuracy:

- the type, number and orientation of RFID antennas
- the number of items transported through the gate at once
- the detailed manner in which RFID tags are attached to their associated item, particularly if the item is metallic or contains liquids

Besides the formal experiments we also performed a series of informal technology demonstrations:

- Agent tracking in and out of the mess-tent: We installed the low frequency (915 MHz) system at the entrance to the Mess-tent and gave out passive tags to all HMP participants on base. Over a continuous period of 3 days we monitored the traffic of personnel in and out of the tent, recording hundreds of transactions. This allowed us to generate individual tracking histories, confirm the amount of traffic around peak times (typically meal times: breakfast, lunch, dinner) by generating histograms of transactions (Fig. 5.15). To do this, we wrote application software in the context of a layered distributed sensing architecture (Fig. 5.4) that updated the location field of agents or supply items in real-time in the SQL database.

- Outdoor ATV tracking: We leveraged this capability, using the high frequency (2450 MHz) system and applied battery assisted tags to the all-terrain vehicles (ATVs). This allowed us to set up an outdoor RFID gate for vehicle monitoring between the ATV Park at the HMP RS and the dirt road leading to the airstrip. Over the course of 3 days we monitored the ATV traffic, and wrote an application that produces real time reports about individual vehicles arrivals and departures as well as overall fleet usage patterns (Fig. 5.17).

- During the technology demonstration experiments we discovered that RF interference issues between the RFID transceivers and the rest of the communications infrastructure on base are real and serious. The concern is not primarily that other equipment could generate spurious RFID transactions, but rather that the RFID system can act as a noise source and jam safety critical communications systems. These issues can be addressed by proper design and tuning of the RFID system. However, rather than implementing RFID and other distributed sensors as an afterthought, they should be integrated into the overall design and operations of the communications infrastructure at the research station.

We also found that RFID could enable more exotic and useful applications, such as the rapid "check-out" of a vehicle for traverse using hand-held readers; by creating "smart shelves" that sense what items are on them, it could also save researchers precious time locating and analyzing rock and soil samples that are obtained during field excursions. Our studies suggest that while RFID technology will undoubtedly save time, basic improvements in accuracy and system design will be needed to justify their cost, mass and complexity. Also, significant development of the middleware between the actual sensors and desired "business applications", see layers 1-3 in Figure 5.4, will be needed. Perhaps more importantly, our experience at HMP has revealed more questions that need to be address before a comprehensive RFID solution for space exploration can be created (see Section 5.5).

7.1.5 EVA Logistics

While much of our work at HMP focused on macro-logistics, i.e. the movement of crew and cargo over large distances (>100 km) to and from base, we also began researching the requirements of micro-logistics. One aspect of micro-logistics is tracking of the movement of people and supply items within and around the vicinity of the base as described in the previous section.

Perhaps more important is the ability of the logistics system to support extravehicular activities (EVAs) away from base. It is these activities that will ultimately generate value through exploration knowledge, scientific insight as well as data (e.g. imagery) and physical samples. We developed a systematic way to describe and record planetary EVAs (Appendix G) and recorded pre- and post-EVA data for 8 such traverses. One of these EVAs into the Haughton Crater is described in detail in this report (Section 6.3). The range of EVAs observed went from two person EVAs on foot to 9 person EVAs using all terrain vehicles (ATVs). We found that supply items taken along on EVAs generally fall into the following categories:

- Excursion Supplies (water, food, …)
- Safety Critical Items (radios, shotguns, ropes, …)
- Exploration Equipment (cameras, sample bags, rock hammers, …)

While specific items might be different for surface exploration on the Moon and Mars, we believe that the categories will be the same. Also, we found that EVAs almost never occurred exactly as planned. This was primarily driven by the uncertainties around the weather and especially the ability to travel pre-planned routes across unknown or partially unknown terrain. While the topography might be well known in advance through maps and aerial or satellite imagery, the detailed soil conditions (e.g. bearing strength) are generally not.

As part of the HMP expedition we derived as set of generic parameters, constraints and objectives that can be used to optimally plan EVAs ahead of time, as well as re-plan them while en-route according to the unfolding situation (Appendix H).

7.2 Analogies between HMP and Lunar/Mars Research Base Logistics

This section addresses the extent of the analogy between HMP and Martian/lunar exploration bases in terms of logistics. Critically analyzing what is analogous and what isn't was one of the key objectives of our expedition (see Section 1). HMP was set up as a 'Mars analog base' in terms of *science* rather than logistics. HMP logistics is accomplished in whatever manner is easiest and/or least expensive. However, due to its remote location, the limited avenues of access to the base, and the similar demands on base infrastructure and supplies (supporting scientific researchers), the analogy between HMP and Martian/lunar base *logistics* is entirely reasonable.

We expect that the analogy is more accurate in some areas than in others. For example, several obvious differences became apparent:

- *HMP uses in-situ water resources.* Water is imported from snow-melt feeding into the Lowell Canal (see Fig. 3.7) nearby, and therefore it is unnecessary to bring in large quantities of water. Furthermore, tracking of water usage rates would be useful, but might be skewed, because water conservation is less necessary than it would be on a Martian or lunar base[40]. The exact water usage at HMP in liters/day is currently unknown, despite sporadic chemical monitoring of the water quality.

- *HMP has more frequent flights (resupply) than a Moon or Mars outpost.* Twin Otter airplanes can be flown in from Resolute Bay any time they are available (not all the time, but generally at least a few times per week, see Appendix F). As a result, crucial consumables or unexpected equipment requirements can be shipped to HMP on relatively short notice, whereas the same is impossible on Mars/Moon. The current schedule for lunar cargo resupply flights foreseen by the Exploration Systems Architecture Study [9, Ch. 4, Fig. 4-62] is based on a 6-month resupply schedule, similar to ISS.

- *HMP is relatively 'luxurious' in cooking/eating arrangements.* One of the major categories of inventoried supplies was food (Fig. 3.3). This is one area where HMP almost certainly differs from Mars/Moon. Because of the relative ease of shipments, standard food (e.g. fresh produce) can be flown in. Martian/lunar bases would almost certainly depend on dehydrated foods like those used on ISS today. The shipment masses would therefore be quite different for HMP, where heavy items such as canned food are shipped in. See Section 3.3.2 for a more detailed discussion of this item.

- *Criticality of Stowage Space.* Figure 7.1(a) shows a recently taken picture inside the International Space Station. The availability and management of stowage space has turned out to be one of the most critical aspects of ISS operations. This is also expected to hold true for CEV and planetary exploration habitats. Figure 7.1(b) on the other hand shows the abundance of indoor stowage at HMP. This is primarily driven by the absence of a requirement for pressurized stowage at HMP; much cargo is stored outdoors,

[40] Water usage is actually kept low at HMP, but primarily for reasons of outflow, i.e. attempts are made to minimize the amount of organic matter that seeps into the soil in and around the HMP research station in order not to transform the local ecology.

especially during the field season. Nevertheless, some of the elements at HMP (Fig. 2.3) are crowded due to the need to protect sensitive electronics and other equipment from the elements.

Figure 7.1: (a, left): Criticality of stowage space aboard ISS (source: http://spaceflight.nasa.gov/gallery/index.html); (b, right) inside of MIT tent

Despite these differences, there are many areas in which we find that the analogy between HMP and Lunar/Mars logistics holds up well. These areas are discussed below. In addition, there are still lessons to be learned even in those areas that are recognizably different between HMP and Lunar or Mars bases.

7.3 HMP Analogy Conclusions

Based on the analysis described in Section 3.3, it is clear that our pre-expedition estimate of HMP cargo was relatively accurate, once known differences have been taken into account. The initial estimate predicts HMP stock levels within an order of magnitude for most supply classes. The total estimated mass of the HMP RS and its contents was around 23.7 metric tons, including a 7 metric ton allowance for structural containment, whereas the actual recorded inventory estimated around 20.7 metric tons.

This is a significant achievement, since modeling planetary bases is to-date largely a matter of educated speculation. No planetary bases have been built, and the best real data in existence is from the days of Apollo (with outdated technology and a different mission format) or by analogy with ISS which is a large micro-gravity facility. The data gathered at HMP allows surface expedition modeling relationships to be tested and verified against another set of real data on remote bases (with acknowledged differences between Earth-based and planetary setups). The lack of significant *unexplainable* differences between the lunar/Mars models and the HMP data suggests that the models are acceptable predictors of planetary base surface mission requirements, but that substantial refinement and additional parametric modeling will be required in the future.

Table 7.2 summarizes the classes of supply we found to be analogous or clearly non-analogous between HMP (regardless of their actual mass or quantity) relative to a lunar or Martian base:

Table 7.2: Qualitative List of Analogous and Non-Analogous Supply Classes at HMP

Analogous COS w/Lunar or Mars	Not Analogous COS w/Lunar or Mars
2.4-2.6 Hygiene Items, Personal Items	1.1-1.4 Types of Fuel used
3.1 Office Equipment	2.2 Food and Support Equipment
3.3 Health Equipment, Telemedicine kit	3.2 EVA Equipment & Consumables*
3.5 Communications gear (C-band sat xpdr)	4.1-2 Spares and Maintenance Tools
6.2 Field Research Equipment (cameras, …)	7.2 Waste Management System
6.3 Rock samples	8.2-8.4 ECLSS, Thermal, Habitation
8.1 Photovoltaic power system (Greenhouse)	
9.1 ATVs (except for combustion engine)	
9.2 Pressurized Rover	
10.1 Public Affairs items (flags etc..)	

* With the exception of EVA suits brought in for testing, these, however, can also be classified under COS 6.1

With some understanding of the inherent differences between HMP and planetary bases, the inventory data from HMP can be partially understood as analogous to lunar/Martian exploration bases. The lessons learned from field operations and the complications of logistics in remote environments are also analogous to the difficulties that we must expect on planetary bases. Thus, we view the combined products (data, field observations, and experience) of MIT's research at HMP in 2005 as a good entry point for research in the area of logistics for future planetary bases on the Moon and Mars.

7.4 Recommendations for HMP and Exploration Logistics

This section summarizes our recommendations coming out of the HMP 2005 expedition. The first set of recommendations applies specifically to HMP, while the second set applies more generally to NASA and its implementation of the Vision for Space Exploration (VSE):

7.4.1 Recommendations for HMP Logistics

In the following we summarize some of our recommendations for HMP crew and cargo logistics:

1. It would be better if detailed information about *cargo weights would be gathered beforehand and used for scheduling (not only crew scheduling)*. This would allow planners to more accurately arrange contracts before the field season, potentially with built-in options for additional flights.

2. There should be efforts made to *smooth out the HMP campaign schedule* so that it appears more like a boxcar, rather than the triangular distribution of Figure 4.4. This would avoid congestion at the research station during peak times, but also allow a more effective scheduling of flights such that Twin Otters would be loaded with passengers both on inbound as well as outbound flights, rather than the asymmetrical use of the airplanes which is apparent from Figure 4.3 and Table 4.3.

3. Also, we recommend a more orderly *staging process at Resolute and the establishment of a formal reverse logistics staging area at the airstrip at HMP*. This staging area could hold waste, empty fuel drums and other items for reverse logistics such that most flights from HMP back to Resolute would be carrying reverse logistics cargo. If reverse logistics items were held over the winter at this staging area, they could be shipped back with the initial flights (see flights 1-14 in Table 4.3) of the following field season.

4. Many of the challenges in HMP logistics appear to be driven by the short term funding commitments that are made by various sponsors on a year-to-year basis. We recommend ensuring *a sustained, long-term funding and logistics planning model for HMP* that would allow multi-year buys, rental of a warehouse at Resolute and potential use of the barge from Quebec to Resolute for large shipments of bulk items.[41]

5. Broader *cooperation with other Arctic research projects* could leverage economies of scale. Our observation is that HMP could benefit from cooperation with other projects in the logistics area. This cooperation could extend to other research projects on Devon Island, or in the context of a "network of analog sites" being developed by CSA.[42] Cooperation can take the form of joint charter agreements, joint use of warehouse facilities, pooling of ATV spares and consumables or other sharing of resources. Cooperation in this area also requires clear accountability, financial agreements, mutual trust and a common set of rules regarding supply priorities should competing needs arise.

6. We believe that the proper *management of Fuels and Propellants at the HMP airstrip* is the most important safety critical logistics item to be improved. As discussed in this report there are at least four different types of fuel used at the HMP RS (Fig. 3.5), which are distributed at different locations around base (Fig. 3.6). We found that the drums and type of fuel in them often do not correspond to standard international markings. This could have dangerous consequences, e.g. if a Twin Otter were inadvertently refueled with the wrong propellant.

7. We recommend that HMP adopt *a web-based logistics planning infrastructure*. This will facilitate coordinating schedules and logistics for the various research teams. The implementation and use of the online SQL HMP inventory database for planning of the HMP 2006 campaign would be a first step in this direction.

8. We identified the in-situ use of water on Devon Island as one of the biggest differences between HMP and a Lunar and potentially a Martian base. To quantify water usage and quality at HMP in real time, *we recommend installing a water flow meter and gauging system at the inflow to the HMP base camp*. Water readings should be taken twice a day starting in HMP 2006.

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[41] Currently, items would have to be shipped nearly 2 years in advance using the barge service. This, however, could be cost effective and open up entirely new avenues for HMP infrastructure. In some ways such a slow, but large capacity transportation mode is analogous to using an electric propulsion tug in space.

[42] HMP is one of three sites selected in the CSA analog network. The other two sites are situated on Axel Heiberg Island and in British Columbia.

7.4.2 *Recommendations for NASA Exploration Logistics*

1. We found that the existence of multiple, fragmented and partially overlapping databases between NASA Centers and between NASA and its international partners to be one of the major obstacles in current space logistics (Space Shuttle, ISS). This will only get more accentuated as the number of nodes in the interplanetary supply chain increases in the future. *NASA should focus on developing an integrated, relational web-based database for space exploration logistics*. This database could be a further development of IMS, but should also incorporate a comprehensive view of objects, processes and attributes as shown in Section 3.4. All users (astronauts, mission controllers, load masters, vendors, procurers, and logistics planners) should access the same data, albeit through customized interfaces (see Appendix E).

2. The way in which supply items are currently organized in civilian and military organizations as well as the CCART system for ISS is not consistent. Some categories are chosen according to organizational boundaries, others according to the type of material, source node or intended use. *We recommend that NASA adopt a function-based classes-of-supply (COS) system*, similar to the one developed for this project (Fig. 3.1, Table 3.1). These classes can then be further broken down into sub-classes (Table B.6) and ultimately supply types and individual supply items.

3. Further *research into the use of RFID, and distributed sensing more generally, is recommended*. This technology holds the promise to provide real-time updates to the current locations, operational status and fill levels of supply items at a research base. The technology (tags, readers, containers …) needs to be further refined, and integrated into vehicle (e.g. CEV) and habitat design right from the beginning (Section 5). RF Interference issues can be significant and need to be addressed. Much work is also needed in creating a robust middleware (layers 1-3 in Fig. 5.4) that turns raw sensor data into useful applications for intelligent monitoring and planning applications.

4. We found – based on our experience at HMP – that there are major uncertainties as to the operational status of supply items that are left unattended at an exploration node or research station in a space logistics network. We may know that electronic equipment and food consumables have been shipped to a particular location, and that inventory is sufficient. If, however, this location is subject to severe temperature variations (over 50 degrees Celsius at HMP) and other environmental impacts, logisticians may not trust that particular items are still fit for use. As a consequence *NASA should invest in research and new technologies that allow sensitive equipment, food and other supplies to survive harsh conditions on Earth, the Moon and Mars* for extended periods.

5. One of the insights from HMP 2005 was that parent-child relationships in exploration logistics have to be very carefully managed. Unlike commercial supply chains, where products are assembled, packaged and shipped to retail stores, exploration supplies are often carefully packaged and encased at multiple levels. Items that are related (e.g. a telemedicine kit), can be used in one location one day, then moved, repackaged and used

in a different way the next way. *New concepts and technologies must be developed to dynamically track parent-child relationships in exploration logistics*.

6. *HMP is a valuable resource and should be further developed and funded, perhaps in the context of a larger network of Moon- and Mars-analog sites on Earth*. While some parameters are clearly different (gravity, temperatures, presence of water, atmosphere), others are quite similar to Mars and the Moon (terrain, topological features, remoteness, thin supply line, communications delays, type of science performed such as planetary geology). Moreover, HMP and other analog sites provide a relatively low cost, low risk environment to test new technologies, systems and procedures on Earth, before they are deployed on the Moon and Mars. If tests fail or equipment breaks, further iterations and improvements can be done quickly and relatively inexpensively. From an exploration logistics perspective we found that HMP is an ideal, albeit challenging, environment for agent and asset tracking research because it:

    a. represents a “semi-closed” environment similar to a lunar or Martian research station
    b. features a rich, yet manageable set of agents (people), supply items and vehicles to track and analyze
    c. is subjected to varying temperature, dust and weather conditions that stress equipment, often to the breaking point
    d. provides for natural usage patterns of equipment, vehicles, consumables and people movements in the context of an analog planetary exploration base.

7. Planetary surface mobility (see Section 6) will be one of the key drivers of exploration productivity on the Moon and Mars. *NASA should consider new, perhaps non-conventional concepts for planetary surface mobility (micro-logistics).* Examples of such concepts are provided in the next section.

7.5 Future Opportunities and Plans

Our foray into planetary surface analog activities and logistics was extremely fruitful. In addition to the specific accomplishments detailed in this report, the 2005 MIT HMP expedition reinforced certain basic principles of analog research. Specifically, two elements are critical to justify the expense of working at a remote site such as HMP and must be considered in planning future activities:

- The nature of the analogy with other planetary surface exploration must be clear, and the research plan must specify how to translate lessons learned from analog activities into lessons for future planetary exploration.
- The specific characteristics of the analog site must contribute to the type of research being carried out.

Possible ideas for our future involvement in the Haughton-Mars Project include[43]:

[43] We will expand upon a few of these ideas below.

- More comprehensive RFID instrumentation and testing
- Inventory management using the concept of an "Information Kiosk"
- RAMSES – agent and asset tracking infrastructure[44]
- Autonomous, human-robotic interaction work
- Unmanned Rover Testing (related to MIT capstone design courses)
- Spacesuit experiments
- Modular platform-based planetary camper
- Logistics analysis and planning for a network of CSA designated Mars-analog sites, including Axel Heiberg Island and BC.

7.5.1 Proposed Plan for HMP 2006 Expedition (included in Phase II of this project)

In the future we intend to refine the model of the Haughton-Mars Project (HMP) supply chain in terms of its exploration logistics at the macro scale (cargo flow to and from base camp) as well as at the micro scale (cargo flow for EVA traverses) that was started at HMP 2005. This includes both off-line modeling of the logistics (forward and reverse flows), but also additional field observation.

The specific tasks for HMP logistics in 2006 are:

1. Refining classes and sub-classes of supply in the field. As mentioned in Section 3, also in Appendix C and D, we inventoried 2300 items at HMP, but this does not yet represent a complete inventory, e.g. the erected structures have not yet been catalogued. We want to refine the mass estimates provided here (Appendix C,D), but also include volume estimates, especially for bulk items. Future work will establish a complete inventory of HMP at a similar level of detail than what currently exists for ISS.

2. Verify and expand the network model to the entire HMP supply chain. As mentioned in Section 4, our analysis in 2005 focused almost exclusively on arc 3-5 between Resolute and the HMP RS. Future work will create a more comprehensive model for the entire network (Fig. 4.1) and also include the effect of warehouses, inventory holding costs and potentially other Moon/Mars-analog sites in the Arctic region.

3. Validate RFID tagging, reading and automated database management (via local wireless network, potentially via internet) processes during the 2006 summer field season. We would like to expand the RFID experiments to install readers at several modules and install an "information kiosk" in the central, octagonal core (Fig. 2.3).[45]

4. Refine logistics requirements for EVAs, including short traverses and longer excursions with overnight stays away from base camp. As discussed in Section 6, we observed 8 EVAs in 2005. However, these did not include overnight EVAs. In 2006 we plan to further refine our micro-logistics modeling efforts to include overnight EVAs, the

[44] Our research team was selected for a NASA STTR on the topic of Rule-based analytic Asset Management for Space Exploration Systems (RAMSES), FY 2006. The impetus for this project came from HMP 2005.
[45] One of the expansion plans for HMP in 2006 is to connect the modules to the central core with enclosed walkways (see Fig. 2.3). These connectors would be ideal locations for RFID instrumentation.

possibility of air-dropping caches at “optimal” locations in the Haughton Crater and begin quantifying requirements for future surface mobility architectures (see below). Also we seek a better understanding of the interactions between macro-logistics and micro-logistics.

7.5.2 Surface Mobility – (Rover Testing and Modular Platform-Based Planetary Campers)

Our 2005 experience was limited to one-day excursions. Effective planetary surface exploration will certainly involve extended, overnight exploration, which carries extra logistical requirements, both at the macro- and micro-level.

The productivity of crewmembers at a remote exploration site (such as HMP) is strongly driven by their mobility capability. This was recognized very early in the first human lunar exploration program. In Apollo 14 and onwards, the Lunar Roving Vehicle (LRV) was used, which enhanced the radius of exploration by an order of magnitude (see Table 7.3).

Table 7.3: Maximum Distance Traversed by Astronauts Away from Lunar Module

Mission	Max distance [m]
Apollo 11	61
Apollo 12	411
Apollo 14	1454
Apollo 15	5020
Apollo 16	4600
Apollo 17	7629

The LRV was a light, open vehicle that was useful for transporting crew and cargo over short distances (Fig. 7.2a). However, only a few kilometers of traverse were feasible with this unpressurized vehicle. For longer range traverses, which would be essential in any long duration exploration mission on the Moon or Mars, mobility configurations would be required that provide both habitability and transportation functionality.

In the last few decades, several concepts for pressurized rovers and mobile habitats have been proposed. NASA’s Johnson Space Center produced a study in 1990 from its Lunar and Mars Exploration Office showing a pressurized lunar rover vehicle (Fig. 7.2b). This had been based on earlier requirements of a study by Davidson (1988) [10]. Most of these ideas, however, involve very heavy vehicles (several tons in mass), and large volumes. Commonly proposed designs of pressurized rovers are based on 2-6 passenger vehicles that can provide life support on average for 10-14 days (a lunar day). They are typically assumed to carry a large amount of payload (several hundred kilograms) and include various amenities for the crew. The total predicted mass normally ranges from 3 to 7 metric tons. According to NASA’s own assessment a pressurized rover may not be the ideal solution after all: “NASA has examined pressurized rover designs for many years, but such vehicles may be too big and expensive at least for the initial series of future lunar missions”. [11]

Figure 7.2: (a) left: Lunar Roving Vehicle (2 crew, 200 kg empty mass, payload mass: 490 kg, range: 65 km; (b) right: Pressurized Rover Design (2-6 crew, 5,110 kg empty mass range: several 100 km), Source: NASA

These concepts, however, are also not attractive from a logistical and operational perspective. Firstly, bringing such a large monolithic system to a planetary surface will be a very challenging problem for a mass and volume constrained space transportation vehicle. The deployment and setup can also prove to be difficult [12]. Lastly, in the operations phase, handling and safely maneuvering a large, heavy vehicle may be extremely risky and difficult.

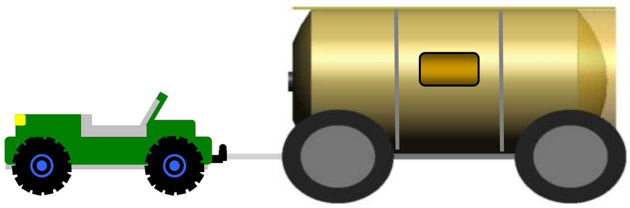
Our experiences this year (2005) at HMP on a simulated EVA with the Humvee (which is meant to simulate a pressurized vehicle used for overnight excursions from the base) have confirmed some of these potential risks. The Humvee often had sinkage problems (even when mounted with caterpillar tracks). Its relatively low agility in realistic terrain greatly hampered the exploration experience, and the vehicle did not fully deliver its intended value (see Fig. 7.3) during this particular campaign.

Keeping all these issues in view, a new concept of a *planetary camper* that can address these important needs should be seriously considered. Such a vehicle is designated as a *camper* since the architectural and design philosophy will be based on the notion of *camping sorties* that the crew will undertake from their main base. Thus, this vehicle would be easily transportable to its destination (both during in-space transfer and subsequently on the planetary surface), and towed by ATVs on rough uncharted terrain.

Figure 7.3: Humvee stuck at HMP (July 2005)

Figure 7.4 shows the ATV and camper towing concept. The table on the right gives estimates of mass and power of the vehicle based on a preliminary design study (Draper/MIT CE&R Study

2005) [7]. We note that the estimated total camper mass of 1262 kg (~ 2800 lbs) could potentially fit on a single Twin Otter flight from Resolute to HMP, provided that the vehicle be built in modular sections.



Total Camper Mass [kg]	1262
Power [kW]	1.4
Wheel Base [m]	3.12
Tread [m]	2.4
Height [m]	3.1
No. of Passengers	2
Crew Free Vol [m^3]	5.18
Extra payload capacity [kg]	300

Figure 7.4: (a) left: Modular Platform-based Planetary Camper (MPPC) in Towing Configuration with an ATV; (b) Right: Design Estimates for a proposed Camper Design.

In order to keep the camper light and low in complexity, the baseline concept would be a minimal vehicle with no drive system of its own and only a small power system for basic life support. The camper would provide a pressurized habitable volume capable of supporting a few crewmembers (perhaps between 2-4 people) for long-range excursions from the main base.

Since the camper would not have a drive system of its own, an ATV would be used for towing it to its desired destination Currently on Earth, ATV's exist with towing capacities of 1500 lbs and more (e.g. Polaris 700). This mobility configuration would enable the crew to make trips from the main base to various sites of interest. In each trip, the camper would be towed to an exploration site and would allow the crew to setup 'camp' for a few days in a particular location or be more nomadic and stay overnight at a different place every night. The ATVs would then be used for local exploration around the 'camp-site'. If a certain site proves to be of greater interest and it is desired to increase the duration of stay, the crew could make a trip back to the base (on the ATVs only) to bring more supplies for the camper. This configuration would provide over-night stay capability to the exploration mission while also having flexibility in mobility and stay-duration options. HMP and the Haughton Crater would provide an ideal context to test such operational exploration scenarios in the future.

In the past, HMP has used the multi-track Humvee for overnight excursions. This vehicle combined habitability and mobility functions. When the vehicle got stuck (Fig. 7.3), or when it broke down, crews were left stranded and could not return to base without individual ATVs. We believe that there is an advantage in separating habitability and mobility functions and would like to pursue the use of a towed, camper-type vehicle for overnight exploration. We envisage developing a modular, platform-based vehicle which can be reconfigured, allowing experimentation with alternate configurations. The vehicle would have to be designed such that experiments at the HMP or other analog environments could be related to ultimate use on planetary surfaces.

Even if they do not get stuck, large habitable vehicles inherently have less mobility than small ATV-type vehicles. Even if a motorized camper vehicle could take a crew to a remote site for overnight excursions, their mobility at that site, and thus their ability to explore, would be

significantly limited if they did not have access to ATVs. If the camper vehicle can be towed to a remote site by an ATV, it can serve as a remote operations base while the crew then takes advantage of the mobility provided by the ATVs to explore the site locally. This puts extra requirements on the ATVs.

The ATVs in use at the HMP Devon Island Base are single person vehicles, in contrast to the two-man Apollo Lunar Rover. The range of the Apollo rover was constrained by the walk-back requirement – the ability of the crew to return to the LEM if the rover broke down – and battery capacity. We believe that single person rovers may offer significant advantages. They do not constrain crew members to stay together and thus, in principle, allow a two person crew to cover more ground. Moreover, if the rovers are capable of carrying two people in an emergency, then the breakdown of a rover is no longer a life-threatening emergency, since the other rover could return the crew to their base. The design of a planetary camper vehicle must be integrated with the design of the towing vehicle. The use of such vehicles on Devon Island requires that they be transportable by a Twin Otter, further constraining the design, but in a way that has clear logistics analogs with planetary exploration.

7.5.3 Spacesuit Experiments

MIT has worked closely over the years with Hamilton Sundstrand Space Systems (HSSS) on various EVA-related activities. Since this was MIT's first summer on Devon Island, and our participation was not finalized until relatively late, we were not involved in the advanced planning for the HSSS's 2005 spacesuit activities, although we participated in them. If HSSS continues their Devon Island operations, we will plan to work with them during the planning phases, in order to improve the operational functionality of the test equipment and to integrate spacesuit testing activities into the other surface operations research described above.

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Appendix A: Fact Sheet for the HMP Project

Fact Sheet: Nunavut, Resolute Bay, Devon Island, Haughton-Mars Project

Nunavut Territory, Canada	
Date of Confederation	April 1, 1999
Capital	Iqaluit
Area	1,994,000 sq km
Population	29,000
Industries	Government, Mining, Tourism, Fishing
GDP	~ $700 million

Resolute Bay	
Location	74°42’N, 94°50’ W, Cornwallis Island
Annual Rainfall	5.3 cm
Population	~200
Economy	Logistics, Mining, Hunting
Founded	1947, (Military Base)
Prior History	Thule Settlement (~1100 AD)

Devon Island	
Location	approx. 75°’N, 90°’ W
Area	55,247 sq km
(Human) Population	0 – largest uninhabited island on Earth
Climate	Polar Desert, 4 cm of rain/year

Haughton-Mars Project	
Goal	Science and Exploration Field Research
Sponsors	Canadian Space Agency, NASA, others
Founded	1997
Active Field Seasons	9
Founder	Dr. Pascal Lee
Location	Devon Island, Nunavut, Canada

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Appendix B: Classes of Supply Validation

Supply classification serves to collect logistics relevant items of a similar nature within groups with similar attributes. These attributes permit consistent management of supply items within a logistics system. Common groupings of supply items might be by:

Table B.1: Attributes for Supply Item classification

Destination	ISS, Moon, Mars
Supplying Organization	Russia, US, ESA, JAXA, Commercial
Intended Use	Research, Maintenance, Operations
Transportation Mode	Rail, Shuttle, Progress, ATV, HTV, CEV
Main Function (similar to Intended Use)	Consumables, Science, Spares, Crew Provisions, Medical Material, Construction Material, Weapons, Waste Management, Field Safety
Inherent Properties	Class III – Petroleum and Other Liquids; Federal Supply Class #1120 Nuclear Depth Charges
Direction of Travel	Supply, Return, Up, Down, Transfer
Environmental Needs, Storage Requirements	Pressurized, Un-pressurized, Wet, Dry, R/F Food, Ambient Food, etc
Packaging	Containerized, Unit pack, Bulk Pack, Loose Pack, Pantry
Consumption Rate	e.g. Daily, Weekly, Monthly, per EVA, per Launch…
Type of Consumable	Solid, Liquid, Gaseous etc. e.g. class for ammunition, class for petroleum
Handling Requirements	class for collective cargo, special handling cargo, carried with people
Criticality Level	e.g. priority level classification of spare parts in submarines

Further decomposition within the classes may be provided by sub-classes or categories. We conducted a careful analysis of the classifications used by a number of organizations such as NATO (Table B.2) and the U.S. Military (Table B.3). Detailed comments are provided below, but it is interesting to note that classifications are inconsistent between organizations, primarily because different priority is given to the classification attributes (Table B.1) and because mission needs are different. From this comparison we are left with two primary conclusions:

1. A <u>relational database</u> structure will be most useful as this allows organizing the classes of supply dynamically, depending on use cases (logistics planner, astronaut, mission control). This is essential to avoid misalignment of classification schemes between different organizations in the interplanetary supply chain.

2. The <u>functional classification</u> proposed here (Figure 3.1, Table 3.1) and refined at HMP is the most consistent high-level classification as it is independent of organizational boundaries and specific supply item or mission requirements.

Table B.2: Classes of Supply Used by NATO[46]

Chapter 1: NATO Logistics

Annex A

Classes of Supply

NATO classes of supply are established in the five-class system of identification as follows:

Class I

Items of subsistence, e.g. food and forage, which are consumed by personnel or animals at an approximately uniform rate, irrespective of local changes in combat or terrain conditions.

Class II

Supplies for which allowances are established by tables of organization and equipment, e.g. clothing, weapons, tools, spare parts, vehicles.

Class III

Petroleum, oil and lubricants (POL) for all purposes, except for operating aircraft or for use in weapons such as flamethrowers, e.g. gasoline, fuel oil, greases, coal and coke.
(**Class IIIa** - aviation fuel and lubricants)

Class IV

Supplies for which initial issue allowances are not prescribed by approved issue tables. Normally includes fortification and construction materials, as well as additional quantities of items identical to those authorized for initial issue (Class II) such as additional vehicles.

Class V

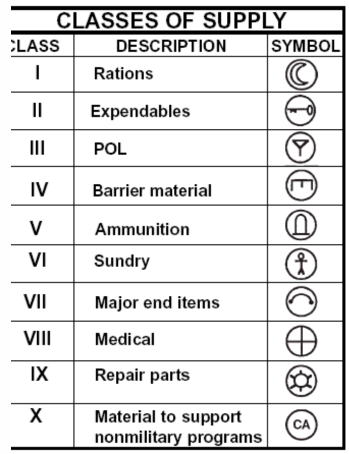
Ammunition, explosives and chemical agents of all types.

[46] Source: <http://www.nato.int/docu/logi-en/1997/lo-01a.htm>

Comments: Class I and III deal with consumables required for essential existence and operations (i.e. to support life), Class V deals with consumables of the essential function (which is warfare), while Class II and IV complement each other for everything else.

Table B.3 Classes of Supply Used by the US Military[47]

Class	Supplies
I	Subsistence, gratuitous health and comfort items.
II	Clothing, individual equipment, tentage, organizational tool sets and kits, hand tools, unclassified maps, administrative and housekeeping supplies and equipment.
III	Petroleum, fuels, lubricants, hydraulic and insulating oils, preservatives, liquids and gases, bulk chemical products, coolants, deicer and antifreeze compounds, components, and additives of petroleum and chemical products, and coal.
IV	Construction materials, including installed equipment, and all fortification and barrier materials.
V	Ammunition of all types, bombs, explosives, mines, fuzes, detonators, pyrotechnics, missiles, rockets, propellants, and associated items.
VI	Personal demand items (such as health and hygiene products, soaps and toothpaste, writing material, snack food, beverages, cigarettes, batteries, and cameras—nonmilitary sales items).
VII	Major end items such as launchers, tanks, mobile machine shops, and vehicles.
VIII	Medical materiel including repair parts peculiar to medical equipment.
IX	Repair parts and components to include kits, assemblies, and subassemblies (repairable or non-repairable) required for maintenance support of all equipment.
X	Material to support nonmilitary programs such as agriculture and economic development (not included in Classes I through IX).
Miscellaneous	Water, salvage, and captured material.



CLASSES OF SUPPLY

CLASS	DESCRIPTION	SYMBOL
I	Rations	
II	Expendables	
III	POL	
IV	Barrier material	
V	Ammunition	
VI	Sundry	
VII	Major end items	
VIII	Medical	
IX	Repair parts	
X	Material to support nonmilitary programs	CA

Comments: Class I, II, VI, and VIII relate to personnel (objects needed for their life, life-maintenance processes), in this set I and VIII are most critical followed by II and VI. Class III and IV are based on the type of material (work fluids, construction materials), class V are solid consumables of the essential function (warfare), class VII are objects required for the essential function (warfare). Class IX is spare parts for all objects, so it has a general function of supporting functioning (maintenance and repair) of all equipment. There is no consistent classification scheme here. Some are based on type of material (e.g. class III), while others are based on type of function (e.g. class VII), and still others are based on the consumer/user of the objects (e.g. class I in which the personnel directly consume and use the items in this category).

As far as manned space flight goes, there are no supply classes used by NASA in the traditional sense. Each program has developed categories used in manifest planning, cargo planning, and stowage planning. The categories match up primarily with organizational structures and are different in each program. Since the operational requirements are different in the Space Shuttle Program and the International Space Station Program, integration has been problematic, resource

[47] Source: <http://www.globalsecurity.org/military/library/policy/army/fm/4-0/chap6.htm#6-2>

planning has suffered, and the organizational structure has actually grown in both programs to cover communication between programs. On the International Space Station (ISS), a known system of supply classification is used – at least on the U.S. side. This system is referred to as the Cargo Category Allocation Rates Table (CCART). Table B.4 reproduces the classification of cargo items on the International Space Station with some examples provided.

Table B.4 Cargo Categories Used for ISS: CCART

1. CREW PROVISIONS	**5. STATION SYSTEMS SUPPORT**
1.1 Joint Crew Provisions	**5.1 US Station Systems**
clothing	IVA tools: utility light, tape
hygiene	maintenance spares: O-rings
care packages	ECLSS: LiOH canisters
1.2 Crew Provisions/Food	Extravehicular Robotics (EVR)
US food containers	**5.2 Russian Station Systems**
Russian food containers	IVA tools
utensils	maintenance spares
2. CREW DAILY OPERATIONS	ECLSS: LiOH canisters
2.1 Joint Crew Dialy Operations	dust Collector cartridge
office supplies	**5.3 FGB Station Systems**
2.2 US Crew Daily Operations	FGB IVA tools
computers	FGB Maintenance spares
vaccum cleaners	**6. EVA**
film cassette	**6.1 US EVA**
batteries	EVA suits and consumables
2.3 Russian Crew Daily Operations	EVA tools
laptops	**6.2 Russian EVA**
dust collectors	EVA Orlan suits and consumables
photo equipment/consumables	EVA tools
electrical pow er system	**7. USERS/PAYLOADS**
3. INTEGRATED MEDICAL SYSTEM	JAXA utilization
3.1 US ISS Medical Equipment	ESA utilization
microbial air sampler	**8. WASTE MANAGEMENT**
blood pressure/electrocardiograph	black polyliner bags
defibrillator resupply kit	crumb bags
crew care packages	solid w aste container
3.2 Russian ISS Medical Equipment	**9. SDTO**
medical first aid kits	**10. INGRESS/DOCKING EQUIPMENT**
dosimeter (radiation)	**11. VISTING VEHICLES/CARRIES**
cardiorecorder Accessory kit	11.1 Shuttle hardw are
4. WATER TRANSFER	11.2 Soyuz equipment
EDVs	**12. STATION ASSEMBLY/ OUTFITTING INTERNAL - MODULES/HARDWARE**
CWCs	**13. STATION ASSEMBLY/ OUTFITTING EXTERNAL ELEMENT and TRUSS HARDWARE**
	14. MULTIPLE CATEGORIES

Comments: The above table lists all the top level categories (but not all the sub-categories). Apart from the common categories such as *crew provisions* there are some that are based on a particular function (e.g. EVA, Payloads), some based on utility of material (e.g. waste management, which deals with all discarded/useless material), and some based on a specific material itself (e.g. water transfer).

We have conducted a mapping between the CCART system and our proposed functional classification of COS. This is shown in Table B.5. The 10 COS of the functional classification can capture all major CCART items for ISS, but also include propellants and fuels (COS 1), transportation vehicles such as ATVs (COS 9) and science and exploration equipment (COS 6) that would be used on a planetary surface as well as other items that might need to be provided in support of a remote exploration station.

Table B.5: Mapping between functional COS and CCART

Classes	Sub-Classes	CCART categories
1. Propellants	101 Cryogens (liquid oxygen, liquid hydrogen etc)	
	102 Hypergols (hydrazine, nitrogen tetraoxide etc)	
	103 Nuclear Fuel	
	104 Petroleum Fuels	
	105 Other Fuels (water/ethylene-glycol etc.)	
2. Crew Provisions	201 Water and support Equipment	4
	202 Food and support Equipment	1.2.1, 1.2.2, 1.2.3
	203 Gases (oxygen, nitrogen etc)	5.2.5,
	204 Hygiene Items (toothpaste, soap, toilet paper, etc)	1.1.3, 1.1.4, 2.2.4
	205 Clothing	1.1.2
	206 Personal items	1.1.5, 3.1.4, 1.1.6, 1.1.1
3. Crew Operations	301 Office equipment and supplies (laptops, stationery etc)	2.1.1, 2.2.2
	302 EVA equipment & consumables	6.1.1, 6.1.2, 6.1.3, 6.1.4
	303 Health equipment & consumables	3.1.1, 3.1.2, 3.1.3
	304 Safety equipment (gas masks, fire extinguishers, contamination protection items etc)	
	305 Communications equipment	2.2.10, 2.2.9
	306 Computers and Support equipment	2.1.2, 2.2.1
4. Maintenance and Upkeep	401 Spares and Repair parts	5.1.2, 5.1.3, 5.1.4
	402 Maintenance Tools	5.1.1
	403 Lubricants, bulk chemicals (alcohols, refrigerants etc)	
	404 Batteries (expendable power modules)	2.2.6
	405 Cleaning Equipment and Consumables (vaccum bags, detergents, filters etc)	2.2.3
5. Stowage and Restraint	5.1 Cargo Transfer Bags (CTB), Containers, Bungees, fasteners, restraints etc	2.2.7
	5.2 Inventory management equipment (bar code readers, RFID equipment, etc.)	Next Generation of 2.1.3
6. Exploration Items	6.1 Science Instruments	
	6.2 Field Equipment (tools, cameras, Photo TV Equipment, etc)	2.2.5, 5.1.7
	6.3 Samples (cores, rocks, etc)	
	6.4 Experiment/Monitoring Stations	
	6.5 Robots/Robotic Rovers	
7. Waste	7.1 Waste	8.2
	7.2 Waste management equipment	8.1
8. Capital Goods	infrastructure/assests for habitability, storage, power generation, resource production etc	12, 13, 5.1.5, 5.1.6
9. Carriers		11
10. Miscellaneous	Public affairs and outreach	2.2.8
		2.11, 2.12, 2.13 will be distributed on an item specific basis in various categories

This leads to the following functional 10 classes of supply (COS) and 44 sub-classes of supply for space exploration logistics. This is also the classification we have used for the HMP 2005 expedition.

Table B.6: COS and sub-classes of supply

1-[Propellants & Fuels]	101-[Cryogens (liquid oxygen, liquid hydrogen etc)]
	102-[Hypergols (hydrazine, nitrogen tetraoxide etc)]
	103-[Nuclear Fuel]
	104-[Petroleum Fuels]
	105-[Other Fuels (water/ethylene-glycol etc.)]
2-[CrewProvisions]	201-[Water and support Equipment]
	202-[Food and support Equipment (mugs,É)]
	203-[Gases (oxygen, nitrogen etc)]
	204-[Hygiene Items (toothpaste, soap, toilet paper, urine bottles, etc)]
	205-[Clothing (incl. shirts, pants, underwear, overalls, sweaters, gloves, pijamas, etc)]
	206-[Personal items (CD-player, DVDs, books, pictures, sleeping bags)]
3-[CrewOperations]	301-[Office equipment and supplies (stationery etc), Documentation (user manuals)]
	302-[EVA equipment & consumables]
	303-[Health equipment & consumables (medical instruments, band aids, cr¸me)]
	304-[Safety equipment (gas masks, fire extinguishers, contamination protection items etc)]
	305-[Communications equipment (transmitters, antennas, ham-radio, walkie-talkie,É)]
	306-[Computers & support equipment (laptops, USB sticks, printer, toners)]
4-[Maintenance & Upkeep]	401-[Spares]
	402-[Maintenance Tools]
	403-[Lubricants, bulk chemicals (alcohols, refrigerants etc), gas (helium, mixtures etc)]
	404-[Batteries (expendable power modules)]
	405-[Cleaning Equipment and Consumables (vaccum bags, detergents, filters etc)]
5-[Stowage & Restraint]	501-[Cargo Transfer Bags (CTB), Containers, Bungees, fasteners, restraints etc]
	502-[Inventory management equipment (bar code readers, RFID equipment, etc.)]
6-[Exploration & Research]	601-[Science Instruments, Technology development testbeds & equipment]
	602-[Field Equipment (tools, cameras, Photo TV Equipment, etc)]
	603-[Samples (cores, rocks, etc)]
	604-[Experiment/Monitoring Stations]
	605-[Field habitation (tents, bivaouc, É)]
	606-[Robotic assistants and support equipment]
7-[Waste Disposal]	701-[Waste]
	702-[Waste management equipment]
8-[Habitation & Infrastructure	801-[Power systems and support equipment (incl. lighting, plugs, cables, chargers)]
	802-[Thermal management and support equipment]
	803-[Life support, air pressure management, CO2 scrubber and support equipment]
	804-[Structural containment, fasteners, apertures & hatches, windows, docking ports]
	805-[ISRU Plants and support equipment (water, oxygen generation, filters, pumps,É)]
	806-[Construction equipment and tools (drills, covers,É), assembly equipment]
9-[Transportation & Carriers]	901-[ATVs, rovers and support equipment (excl. spares)]
	902-[Pressurized rovers and support equipment (excl. spares)]
	903-[Logistics carriers & containers (crates, palettes), visiting vehicles]
10-[Miscellaneous]	1001-[Public affairs and outreach (flags, patches,etc)]
	1002-[Miscellaneous items]

Appendix C: Inventory Database Summary

The following table shows the HMP 2005 inventory data (in kg) broken down by both class of supply (rows) and location on base (columns), where such information was recorded.

Table C.1: (Part 1) HMP Inventory by Class of Supply and Location

		Mass (kg) of Items by Location				
	Class of Supply	**Office Tent (inc. Medical)**	**Waste Management**	**MIT Tent**	**Research Tent 1**	**Core Tent**
1. Propellants and	1.1 Cryogens (liquid oxygen, liquid hydrogen etc)					
	1.2 Hypergols (hydrazine, nitrogen tetraoxide etc)					
	1.3 Nuclear Fuel					
	1.4 Petroleum Fuels				0.2	
	1.5 Other Fuels (water/ethylene-glycol etc.)					
2. Crew Provisions	2.1 Water and support Equipment					
	2.2 Food and support Equipment (mugs,…)	5		0.4		
	2.3 Gases (oxygen, nitrogen etc)					
	2.4 Hygiene Items (toothpaste, soap, toilet paper, urine	0.2				
	2.5 Clothing (incl. shirts, pants, underwear, overalls, sweaters, gloves, pijamas, etc)				4	
	2.6 Personal items (CD-player, DVDs, books, pictures, sleeping bags)			0.1		
3. Crew Operations	3.1 Office equipment and supplies (stationery etc), Doc	9.2		6.3		0.3
	3.2 EVA equipment & consumables				142	
	3.3 Health equipment & consumables (medical instrume	68.8		2		
	3.4 Safety equipment (gas masks, fire extinguishers, co	6.2		0.2	2	0.8
	3.5 Communications equipment (transmitters, antennas	24.4		2		
	3.6 Computers & support equipment (laptops, USB stick	5		2.7		
4. Maintenance an	4.1 Spares	0.2				68.55
	4.2 Maintenance Tools			3.6		58.7
	4.3 Lubricants, bulk chemicals (alcohols, refrigerants et	0.2				109.6
	4.4 Batteries (expendable power modules)	1.2		0.3		
	4.5 Cleaning Equipment and Consumables (vaccum ba	15				0.5
5. Stowage and Re	5.1 Cargo Transfer Bags (CTB), Containers, Bungees, f	99.5		7.5	5	4
	5.2 Inventory management equipment (bar code readers, RFID equipment, e			12.9		
6. Exploration and	6.1 Science Instruments, Technology development testb	0.2				
	6.2 Field Equipment (tools, cameras, Photo TV Equipm	27		0.9	17	
	6.3 Samples (cores, rocks, etc)					
	6.4 Experiment/Monitoring Stations					
	6.5 Field habitation (tents, bivaouc, …)	8			8	
	6.6 Robotic assistants and support equipment					
7. Waste Disposal	7.1 Waste					
	7.2 Waste management equipment		72.2		1	25.3
8. Habitation and I	8.1 Power systems and support equipment (incl. lighting	25.5		5.4	2.2	20
	8.2 Thermal management and support equipment	18		15.2	17	
	8.3 Life support, air pressure management, CO2 scrubb	100		51.2		
	8.4 Structural containment, fasteners, apertures & hatches, windows		20	100.5	110	
	8.5 ISRU Plants and support equipment (water, oxygen generation, filters, pumps,…)					6
	8.6 Construction equipment and tools (drills, covers,…), assembly equipment					106.5
9. Transportation a	9.1 ATV's, rovers and support equipment (excl. spares)	2		1		
	9.2 Pressurized rovers and support equipment (excl. spares)					
	9.3 Logistics carriers & containers (crates, palettes), visiting vehicles					
10. Miscellaneous	10.1 Public affairs and outreach (flags, patches,etc)	53		0.2	1.2	
	10.2 Miscellaneous items				2.5	
	Total by Location	**468.6**	**92.2**	**212.4**	**312.1**	**400.25**

Table C.1: (Part 2) HMP Inventory by Class of Supply and Location

	Class of Supply	Mass (kg) of Items by Location Mess Tent (inc.	Greenhous	Comm Systems Tent	Outdoor	Humvee	Total by COS
1. Propellants and	1.1 Cryogens (liquid oxygen, liquid hydrogen etc)						0
	1.2 Hypergols (hydrazine, nitrogen tetraoxide etc)						0
	1.3 Nuclear Fuel						0
	1.4 Petroleum Fuels	16			4137		4153.2
	1.5 Other Fuels (water/ethylene-glycol etc.)						0
2. Crew Provision	2.1 Water and support Equipment	11					11
	2.2 Food and support Equipment (mugs,…)	2337		6		6	2354.4
	2.3 Gases (oxygen, nitrogen etc)						0
	2.4 Hygiene Items (toothpaste, soap, toilet paper, u		0.5				0.7
	2.5 Clothing (incl. shirts, pants, underwear, overall	59			345.455		408.455
	2.6 Personal items (CD-player, DVDs, books, pictu	32	34		86.3636	6.5	158.964
3. Crew Operation	3.1 Office equipment and supplies (stationery etc),	6	8				29.8
	3.2 EVA equipment & consumables		0.5				142.5
	3.3 Health equipment & consumables (medical ins						70.8
	3.4 Safety equipment (gas masks, fire extinguishe	12	2				23.2
	3.5 Communications equipment (transmitters, ante	37.5	5	119.4		1	189.3
	3.6 Computers & support equipment (laptops, USB		6.5				14.2
4. Maintenance an	4.1 Spares						68.75
	4.2 Maintenance Tools		5			5.2	72.5
	4.3 Lubricants, bulk chemicals (alcohols, refrigerar					4	113.8
	4.4 Batteries (expendable power modules)	0.5					2
	4.5 Cleaning Equipment and Consumables (vaccu	13.5					29
5. Stowage and Re	5.1 Cargo Transfer Bags (CTB), Containers, Bunge	38	6			3.1	163.1
	5.2 Inventory management equipment (bar code readers, RFID equipment, etc.)						12.9
6. Exploration and	6.1 Science Instruments, Technology developmen		1423				1423.2
	6.2 Field Equipment (tools, cameras, Photo TV Eq	0.05	99				143.95
	6.3 Samples (cores, rocks, etc)						0
	6.4 Experiment/Monitoring Stations						0
	6.5 Field habitation (tents, bivaouc, …)		10		129.545		155.545
	6.6 Robotic assistants and support equipment						0
7. Waste Disposal	7.1 Waste				445.5		445.5
	7.2 Waste management equipment	2.9					101.4
8. Habitation and I	8.1 Power systems and support equipment (incl. lig	14.6	10		-	0.4	78.1
	8.2 Thermal management and support equipment	100	33				183.2
	8.3 Life support, air pressure management, CO2 s	2	16			0.5	169.7
	8.4 Structural containment, fasteners, apertures &	173	75		-		478.5
	8.5 ISRU Plants and support equipment (water, oxygen generation, filters, pumps,…)						6
	8.6 Construction equipment and tools (drills, covers,…), assembly equipment						106.5
9. Transportation (	9.1 ATV's, rovers and support equipment (excl. spares)		47		4231		4281
	9.2 Pressurized rovers and support equipment (excl. spares)				4960	64.1	5024.1
	9.3 Logistics carriers & containers (crates, palettes), visiting vehicles						0
10. Miscellaneous	10.1 Public affairs and outreach (flags, patches,etc	12.2	7				73.6
	10.2 Miscellaneous items	26					28.5
	Total by Location	**2893.25**	**1787.5**	**125.4**	**14334.9**	**90.8**	**20717.4**

Note that the mass breakdown shown in this table suggests that the total amount of equipment and supplies at the HMP research station equals roughly 20,717 kg. This, however, does not include the mass of the erected structures.[48]

[48] This recorded inventory of 20.7 metric tons is a lower bound. Based on "ideal packing" a minimum of 19 Twin Otter flights (see Section 4) would be required to remove all equipment from the HMP site, not counting the volume and mass of the erected structures shown in Figure 2.3. The HMP estimate in Fig. 3.8 shows a total mass for habitation and infrastructure of around 7 metric tons, which would require an extra 6 Twin Otter flights for removal.

__Additional Inventory Analysis__

An additional example of analysis that can be performed on the inventory data gathered at HMP, is to separate the inventory by owner (HMP project, MIT, Canadian Space Agency (CSA), etc). Figure C.1 shows the results of this breakdown. As can be seen from the figure, over half of the items at the Haughton-Mars Project research station are owned directly by the Haughton-Mars Project (HMP). These items include office equipment such as desks, lights and power strips, kitchen supplies such as pots, bowls and utensils, tools, and transportation equipment such as the Humvee and the all terrain vehicles (ATVs). The second largest owner is the CSA. CSA has been participating in the Haughton-Mars Project since its inception and has amassed a substantial amount of equipment at the base, primarily in support of their greenhouse. Most of the communications equipment owned by SFU is brought in and out of HMP each field season. This is so because the communications equipment is used for other purposes year-round and the harsh Arctic conditions in the winter time cause the equipment to freeze down to -40 degrees Celsius, with subsequent freeze/thaw cycles in the spring and early summer causing possible damage due to condensation.[49]

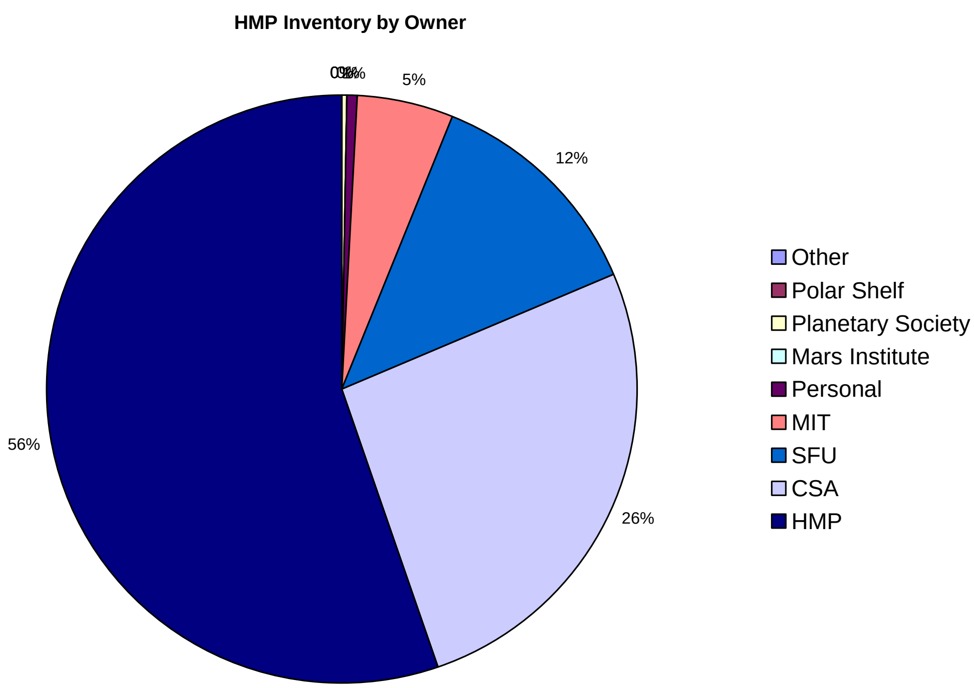


Figure C.1: HMP Inventory by Ownership

[49] A major conclusion from HMP is that sensitive equipment (e.g. electronics) that is permanently installed at a remote base must be designed to withstand extremely cold temperatures, varying humidity levels, thermal stresses caused by freeze/thaw cycles and preferable self-report its operational status via autonomous communications links at regular intervals. Otherwise such equipment must be brought in anew for every field season, as it cannot be trusted to work when first powered up after long periods of non-use.

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Appendix D: Mass Analogy Data for HMP

Table D.1: Detailed Comparison of 3 models with HMP Actuals

DETAILED COMPARISON: Total [kg]

INPUTS	Lunar Long	Lunar Short	HMP Estimate	HMP Actuals
# of crew	**CER [7]**	**CER [7]**	**June 2005**	**according**
19	**baseline**	**baseline**		**to inventory**
Mission Duration	**180 days**	**10 days**		
36				
Total Crew Days:	**684**	**684**	**684**	**683**

1. Propellants and Fuels	**0.0**	**0.0**	**0.0**	**4153.2**
1.1 Cryogens	**0.0**	**0.0**	**0.0**	**0.0**
Lunar Habitat	0.0	0.0	0.0	0.0
Earth Departure Stage LOX + LH2	0.0	0.0	0.0	0.0
Descent Stage CH4 + O2	0.0	0.0	0.0	0.0
1.2 Hypergols	**0.0**	**0.0**	**0.0**	**0.0**
1.3 Nuclear	**0.0**	**0.0**	**0.0**	**0.0**
1.4 Petroleum	**0.0**	**0.0**	**0.0**	**4153.2**
Diesel	0.0	0.0	0.0	see inventory
Gasoline	0.0	0.0	0.0	see inventory
Aviation	0.0	0.0	0.0	see inventory
Propane	0.0	0.0	0.0	see inventory
1.5 Other	**0.0**	**0.0**	**0.0**	**0.0**
Helium	0.0	0.0	0.0	0.0
2. Crew Provisions	**6246.1**	**4325.9**	**4268.9**	**2933.5**
2.1 Water and support equipment	**2428.2**	**2428.2**	**2428.2**	**11.0**
Drinking water (whole mission)	2428.2	2428.2	2428.2	see inventory
2.2 Food and support Equipment	**475.8**	**447.3**	**447.3**	**2354.4**
Dry Food (whole mission)	437.8	437.8	437.8	see inventory
Eating Supplies (cups, utensils,…)	38.0	9.5	9.5	see inventory
2.3 Gases	**1299.6**	**916.6**	**574.6**	**0.0**
Oxygen	957.6	574.6	574.6	0.0
Nitrogen	0.0	0.0	0.0	0.0
buffer gas leakage	342.0	342.0	0.0	0.0
2.4 Hygiene Items	**85.5**	**85.5**	**85.5**	**0.7**
Personal Hygiene Kit	34.2	34.2	34.2	0.0
Hygiene supplies	51.3	51.3	51.3	see inventory
2.5 Clothing	**1311.0**	**87.4**	**372.4**	**408.5**
Clothing (General)	1311.0	87.4	87.4	see inventory
Clothing (Outdoor)	0.0	0.0	285.0	see inventory
2.6 Personal Items	**646.0**	**361.0**	**361.0**	**159.0**
personal stowage	475.0	190.0	190.0	see inventory
sleep provisions	171.0	171.0	171.0	see inventory

3. Crew Operations	**4821.0**	**3777.0**	**1408.0**	**469.8**
3.1 Office equipment and supplies	**380.0**	**190.0**	**285.0**	**29.8**
operations equipment (tape, stationary etc)	380.0	190.0	190.0	see inventory
laptops/computers, peripherals etc.	0.0	0.0	95.0	see inventory
3.2 EVA equipment & consumables	**3666.0**	**3547.0**	**1083.0**	**142.5**
EVA suits	2618.0	2499.0	595.0	see inventory
EVA consumables (LiOH, water etc)	288.0	288.0	288.0	see inventory
EVA work aids	760.0	760.0	200.0	see inventory
3.3 Health equipment & consumables	**750.0**	**15.0**	**15.0**	**70.8**
Medical/Surgical/Dental Suite	500.0	15.0	15.0	see inventory
Medical/Surgical/Dental/Consumables	250.0	0.0	0.0	see inventory
3.4 Safety equipment	**25.0**	**25.0**	**25.0**	**23.2**
Fire Suppression	25.0	25.0	25.0	see inventory
3.5 Communications equipment	**0.0**	**0.0**	**0.0**	**189.3**
3.6 Computers and Support Equipment	**0.0**	**0.0**	**0.0**	**14.2**
4. Maintenance & Upkeep	**4784.0**	**719.9**	**686.6**	**286.1**
4.1 Spares and Repair parts	**3500.0**	**233.3**	**200.0**	**68.8**
Spares	3500.0	233.3	200.0	see inventory
4.2 Maintenance Tools	**1100.0**	**200.0**	**200.0**	**72.5**
hand tools	200.0	100.0	100.0	see inventory
test equipment	300.0	50.0	50.0	see inventory
machine tools	600.0	50.0	50.0	see inventory
4.3 Lubricants, bulk chemicals	**0.0**	**0.0**	**0.0**	**113.8**
4.4 Batteries (expendable power modules)	**0.0**	**0.0**	**0.0**	**2.0**
4.5 Cleaning Equipment and Consumables	**184.0**	**286.6**	**286.6**	**29.0**
vacuum	13.0	13.0	13.0	see inventory
kitchen/oven cleaning supplies	171.0	171.0	171.0	see inventory
disposable wipes	0.0	102.6	102.6	see inventory
5. Stowage & Restraint	**0.0**	**0.0**	**58.0**	**176.0**
5.1 Cargo Transfer Bags (CTB), Containers, fasteners,	**0.0**	**0.0**	**38.0**	**163.1**
	0.0	0.0	38.0	see inventory
5.2 Inventory management equipment	**0.0**	**0.0**	**20.0**	**12.9**
	0.0	0.0	20.0	see inventory
6. Exploration & Research	**3424.5**	**305.5**	**305.5**	**1722.7**
6.1 Science Instruments	**250.0**	**0.0**	**0.0**	**1423.2**
Habitat lab equipment	250.0	0.0	0.0	see inventory
6.2 Field Equipment (tools, cameras, etc)	**530.5**	**205.5**	**205.5**	**144.0**
Field package (camera, mass spec, …)	180.5	180.5	180.5	see inventory
Portable Life Science Instrumentation	50.0	25.0	25.0	see inventory
Drill	300.0	0.0	0.0	see inventory
6.3 Samples (cores, rocks, etc)	**0.0**	**0.0**	**0.0**	**0.0**
6.4 Experiment/Monitoring Stations	**644.0**	**0.0**	**0.0**	**0.0**
MET and seismic monitor	644.0	0.0	0.0	0.0
6.5 Robots/ robotic rovers	**2000.0**	**100.0**	**100.0**	**0.0**

tele-operated/autonomous robots	2000.0	100.0	100.0	0.0
6.6 Field habitation (tents, bivouac, …)	**0.0**	**0.0**	**0.0**	**155.5**
7. Waste & Waste Disposal	**303.2**	**303.2**	**303.2**	**546.9**
7.1 Waste	**77.5**	**77.5**	**77.5**	**445.5**
human solid fecal waste	75.2	75.2	75.2	see inventory
other human waste (hair, nails, skin etc)	2.3	2.3	2.3	see inventory
7.2 Waste management equipment	**225.7**	**225.7**	**225.7**	**101.4**
trash bags	34.2	34.2	34.2	see inventory
waste collection system supplies	34.2	34.2	34.2	see inventory
contingency waste collection supplies	157.3	157.3	157.3	see inventory
8. Habitation and Infrastructure	**2900.0**	**0.0**	**7060.0**	**1022.0**
8.1 Power systems and support equipment (incl. lighting, plugs, cables, chargers)	**2900.0**	**0.0**	**60.0**	**78.1**
Power Plant	2900.0	0.0	60.0	see inventory
8.2 Thermal management and support equipment	**0.0**	**0.0**	**0.0**	**183.2**
8.3 Life support, air pressure management, CO2 scrubber and support equipment	**0.0**	**0.0**	**0.0**	**169.7**
8.4 Structural containment, fasteners, apertures & hatches, windows, docking ports	**0.0**	**0.0**	**7000.0**	**478.5**
Habitat and Lab Modules	0.0	0.0	7000.0	see inventory
8.5 ISRU plants and support equipment (water, oxygen generation, filters, pumps,…)	**0.0**	**0.0**	**0.0**	**6.0**
8.6 Construction equipment and tools (drills, covers,…), assembly equipment	**0.0**	**0.0**	**0.0**	**106.5**
9. Transportation and Carriers	**14000.0**	**600.0**	**9600.0**	**9305.1**
9.1 ATV's, rovers, and support equipment (excl. spares)	**11400.0**	**600.0**	**6600.0**	**4281.0**
All Terrain Vehicles	11400.0	600.0	6600.0	see inventory
9.2 Pressurized rovers and support equipment (excl. spares)	**2600.0**	**0.0**	**3000.0**	**5024.1**
Pressurized Surface Vehicles	2600.0	0.0	3000.0	see inventory
9.3 Logistics carriers & containers (crates, palettes), visiting vehicles	**0.0**	**0.0**	**0.0**	**0.0**
10. Miscellaneous	**50.0**	**50.0**	**50.0**	**102.1**
10.1 Public affairs and outreach (flags, patches, etc.)	**50.0**	**50.0**	**50.0**	**73.6**
10.2 Miscellaneous items	**0.0**	**0.0**	**0.0**	**28.5**
Totals [kg]	**36528.8**	**10081.6**	**23740.3**	**20717.4**

Table D.2a Details of Long and Short Lunar Demand Models (COS 1-5)

		LUNAR LONG-STAY					LUNAR SHORT-STAY				
		Lunar long-stay mission demand model, unmodified, with HMP					Lunar short-stay mission demand model, unmodified, with HMP				
INPUTS											
# of crew		19					19				
Mission Duration		36					36				
crew-days											
Red Stage Dry Mass		11892									
Yellow Stage Dry Mass (4 - levels/ 8 tanks)											
	Un	**Unit Mass**	**Total [kg]**	**Unit [m^3]**	**Total [m^3]**	**Notes**	**Unit Mass**	**Total [kg]**	**Jnit [m^3**	**Total [m^3]**	**Notes**
1. Propellants and Fuels			0								
1.1 Cryogens			**0**								
Lunar Habitat											
Red stage				LOX + LH2		128216					
Yellow stage				CH4 + O2		32475					
1.2 Hypergols			**0**								
1.3 Nuclear			**0**								
1.4 Petroleum			**0**								
Diesel											
Gasoline											
Aviation											
Propane											
1.5 Other			**0**								
Helium											
2. Crew Provisions			6246		16			4326		10	
2.1 Water and support equipment			**2428.2**					**2428.2**			
Drinking water (whole mission)		3.55	2428.2			HSMAD	3.55	2428.2			HSMAD
2.2 Food and support Equipment			**475.76**					**447.26**			
Dry Food (whole mission)		0.64	437.76	0.008	5.472		0.64	437.76	0.008	5.472	
Eating Supplies		2	38	0.014	0.266	HSMAD 18-5	0.5	9.5	0.014	0.266	HSMAD 18-7
2.3 Gases			**1299.6**					**916.56**			
Oxygen (60 day supply)		0.84	957.6			HSMAD 5-16	0.84	574.56			HSMAD 5-16
Nitrogen											
buffer gas leakage		0.5	342			HSMAD pp 459	0.5	342			HSMAD pp 459
2.4 Hygiene Items			**85.5**					**85.5**			
Personal Hygiene Kit		1.8	34.2	0.005	0.095	HSMAD 18-8	1.8	34.2	0.005	0.095	HSMAD 18-7
Hygiene supplies		0.075	51.3	0.0015	1.026	HSMAD 18-8	0.075	51.3	0.0015	1.026	HSMAD 18-7
2.5 Clothing			**1311**					**87.4**			
Clothing (General)		69	1311	0.336	6.384	HSMAD 18-5	4.6	87.4	0.032	0.608	HSMAD 18-7
Clothing (Outdoor)	c										
2.6 Personal Items			**646**					**361**			
personal stowage		25	475		0.75	HSMAD 18-8	10	190		0.75	HSMAD 18-7
sleep provisions		9	171	0.1	1.9	HSMAD 18-8	9	171	0.1	1.9	HSMAD 18-7
3. Crew Operations			4821		26			3777		26	
3.1 Office equipment and supplies			**380**					**190**			
operations equipment (tape, stationary etc)		20	380	0.002	0.038	HSMAD 18-8	10	190	0.002	0.038	HSMAD 18-7
laptops/computers, peripherals etc.	c										
3.2 EVA equipment & consumables			**3666**					**3547**			
EVA suits		119	2618	1	21	HSMAD pp709	119	2499	1	21	HSMAD pp709
EVA consumables (LiOH, water etc)		8	288			HSMAD 22-2	8	288			HSMAD 22-2
EVA work aids		40	760			HSMAD 22-2	40	760			HSMAD 22-2
3.3 Health equipment & consumables			**750**					**15**			
Medical/Surgical/Dental Suite			500		4	HSMAD 18-5		15		4	HSMAD 18-7
Medical/Surgical/Dental/Consumables			250		1.25	HSMAD 18-5		0		1.25	HSMAD 18-7
3.4 Safety equipment			**25**					**25**			
Fire Suppression			25			HSMAD pp472		25			HSMAD pp472
3.5 Communications equipment			**0**					**0**			
3.6 Computers and Support Equipment											
4. Maintenance & Upkeep			4784		8			720		2	
4.1 Spares and Repair parts			**3500**					**233.333333**			
Spares			3500			Table 3-13, 1999 DRM study		233.333333			Table 3-13, 1999
4.2 Maintenance Tools			**1100**					**200**			
hand tools			200		1	HSMAD 18-8		100		0.33	HSMAD 18-7
test equipment			300		1.5	HSMAD 18-8		50		0.15	HSMAD 18-7
machine tools			600		5	HSMAD 18-8		50		0.25	HSMAD 18-7
4.3 Lubricants, bulk chemicals			**0**					**0**			
4.4 Batteries (expendable power modules)			**0**					**0**			
4.5 Cleaning Equipment and Consumables			**184**					**286.6**			
vacuum			13		0.07	HSMAD 18-8		13		0.07	HSMAD 18-7
kitchen/oven cleaning supplies		0.25	171	0.001	0.684	HMSAD 18.4.9, p	0.25	171	0.0018	1.2312	HMSAD 18.3
disposable wipes		0	0	0	0	HSMAD 18-5	0.15	102.6	0.001	0.684	18-7
5. Stowage & Restraint			0					0			
5.1 Cargo Transfer Bags (CTB), Containers, fasteners,			**0**					**0**			
5.2 Inventory management equipment			**0**					**0**			

Table D.2b Details of Long and Short Lunar Demand Models (COS 6-10)

		LUNAR LONG-STAY					LUNAR SHORT-STAY				
		Lunar long-stay mission demand model, unmodified, with HMP crew and duration.					Lunar short-stay mission demand model, unmodified, with HMP crew and duration				
INPUTS											
# of crew		19					19				
Mission Duration		36					36				
crew-days											
Red Stage Dry Mass		11892									
Yellow Stage Dry Mass (4 - levels/ 8 tanks)											
	Un	**Unit Mass**	**Total [kg]**	**Unit [m^3]**	**otal [m^3]**	**Notes**	**Unit Mass**	**Total [kg]**	**Unit [m^3]**	**Total [m^3]**	**Notes**
6. Exploration & Research			3425		0	CE&R control document		306		0	
6.1 Science Instruments			**250**					**0**			
Habitat lab equipment			250					0			
6.2 Field Equipment (tools, cameras, etc)			**530.5**					**205.5**			
Field package (camera, mass spec, v		9.5	180.5				9.5	180.5			
Portable Life Science Instrumentation		25	50				25	25			
Drill			300					0			
6.3 Samples (cores, rocks, etc)			**0**					**0**			
6.4 Experiment/Monitoring Stations			**644**					**0**			
MET and seismic monitor		16.1	644				0	0			
6.5 Robots/ robotic rovers			**2000**					**100**			
tele-operated/autonomous robots			2000					100			
6.6 Field habitation (tents, bivaouc, …)			**0**					**0**			
7. Waste & Waste Disposal			303		2			303		2	
7.1 Waste			**77.52456**					**77.52456**			
human solid fecal waste		0.11	75.24			HSMAD, 5-16	0.11	75.24			HSMAD,
other human waste (hair, nails, skin e		0.00334	2.28456			HSMAD, 5-20	0.00334	2.28456			HSMAD,
7.2 Waste management equipment			**225.72**					**225.72**			
trash bags		0.05	34.2	0.001	0.684	HSMAD 18-8	0.05	34.2	0.001	0.684	HSMAD 1
waste collection system supplies		0.05	34.2	0.0013	0.8892	HSMAD 18-8	0.05	34.2	0.0013	0.8892	
contingency waste collection supplies		0.23	157.32	0.0008	0.5472	HSMAD 18-3	0.23	157.32	0.0008	0.5472	
8. Habitation and Infrastructure			2900		176			0		5	
8.1 Power systems and support equipment (incl. l			**2900**					**0**			
Power Plant			2900			CE&R control document		0			
8.2 Thermal management and support equipment			**0**					**0**			
8.3 Life support, air pressure management, CO2 s			**0**					**0**			
8.4 Structural containment, fasteners, apertures &			**0**					**0**			
Habitat and Lab Modules											
8.5 ISRU plants and support equipment (water, ox			**0**					**0**			
8.6 Construction equipment and tools (drills, cove			**0**					**0**			
9. Transportation and Carriers			14000					600			
9.1 ATV's, rovers, and support equipment (excl. s			**11400**					**600**			
All Terrain Vehicles		600	11400	4.9	93.1	CE&R control docume	600	600	4.9	4.9	CE&R co
9.2 Pressurized rovers and support equipment (ex			**2600**					**0**			
Pressurized Surface Vehicles		1300	2600	41.412	82.824	CE&R control document		0			
9.3 Logistics carriers & containers (crates, palette			**0**					**0**			
10. Miscellaneous			50					50			
10.1 Public affairs and outreach (flags, patches, e			**50**					**50**			
10.2 Miscellaneous items			**0**					**0**			
Total			**36529**					**10082**			

Table D.3a Direct Comparison between HMP (pre-expedition) estimate and Actuals

	HMP ESTIMATE					HMP ACTUALS			
	Estimates for HMP demands based on relationships from the lunar short-stay								
INPUTS									
# of crew			# of EVA suits		5	19			
Mission Duration			# of generators		2	36			
crew-days			# of ATV's		11				
Red Stage Dry Mass			# of Rovers (Humvee)		1				
Yellow Stage Dry Mass (4 - levels/ 8 tanks)			# of habitat modules		7				
	Unit I	**Total [kg]**	**Unit [m^3]**	**Total [m^3**	**Notes**	**Unit Mass**	**Total [kg]**	**Unit [m^3]**	**Total [m^3**
1. Propellants and Fuels		0					4153		
1.1 Cryogens		**0**					**0**		
Lunar Habitat									
Red stage	LOX + LH2								
Yellow stage	CH4 + O2								
1.2 Hypergols		**0**					**0**		
1.3 Nuclear		**0**					**0**		
1.4 Petroleum		**0**					**4153.2**		
Diesel									
Gasoline									
Aviation									
Propane									
1.5 Other	l	**0**					**0**		
Helium									
2. Crew Provisions		4269		10			2934		
2.1 Water and support equipment		**2428.2**					**11**		
Drinking water (whole mission)		2428.2							
2.2 Food and support Equipment		**447.26**					**2354.4**		
Dry Food (whole mission)		437.76	0.008	5.472					
Eating Supplies		9.5	0.014	0.266					
2.3 Gases		**574.56**					**0**		
Oxygen (60 day supply)		574.56							
Nitrogen									
buffer gas leakage									
2.4 Hygiene Items		**85.5**					**0.7**		
Personal Hygiene Kit		34.2	0.005	0.095					
Hygiene supplies		51.3	0.0015	1.026					
2.5 Clothing		**372.4**					**408.4545**		
Clothing (General)		87.4	0.032	0.608					
Clothing (Outdoor)		285							
2.6 Personal Items		**361**					**158.9636**		
personal stowage		190		0.75					
sleep provisions		171	0.1	1.9					
3. Crew Operations		1408		26			470		
3.1 Office equipment and supplies		**285**					**29.8**		
operations equipment (tape, stationar		190	0.002	0.038					
laptops/computers, peripherals etc.		95							
3.2 EVA equipment & consumables		**1083**					**142.5**		
EVA suits		595	1	21					
EVA consumables (LiOH, water etc)		288							
EVA work aids		200							
3.3 Health equipment & consumables		**15**					**70.8**		
Medical/Surgical/Dental Suite		15		4					
Medical/Surgical/Dental/Consumables		0		1.25					
3.4 Safety equipment		**25**					**23.2**		
Fire Suppression		25							
3.5 Communications equipment		**0**					**189.3**		
3.6 Computers and Support Equipment							**14.2**		
4. Maintenance & Upkeep		687		2			286		
4.1 Spares and Repair parts		**200**					68.75		
Spares		200							
4.2 Maintenance Tools		**200**					**72.5**		
hand tools		100		0.33					
test equipment		50		0.15					
machine tools		50		0.25					
4.3 Lubricants, bulk chemicals		**0**					**113.8**		
4.4 Batteries (expendable power modul		**0**					2		
4.5 Cleaning Equipment and Consumal		**286.6**					29		
vacuum		13		0.07					
kitchen/oven cleaning supplies		171	0.0018	1.2312					
disposable wipes		102.6	0.001	0.684					

Table D.3b Direct Comparison between HMP (pre-expedition) estimate and Actuals

	HMP ESTIMATE		HMP ACTUALS
	Estimates for HMP demands based on relationships from the lunar short-stay		
INPUTS			
# of crew	# of EVA suits	5	19
Mission Duration	# of generators	2	36
crew-days	# of ATV's	11	
Red Stage Dry Mass	# of Rovers (Humvee)	1	
Yellow Stage Dry Mass (4 - levels/ 8 tanks)	# of habitat modules	7	

	Unit I	Total [kg]	Unit [m^3]	Total [m^3]	Notes	Unit Mass	Total [kg]	Unit [m^3]	Total [m^3]
5. Stowage & Restraint		58					176		
5.1 Cargo Transfer Bags (CTB), Contai		**38**					**163.1**		
		38							
5.2 Inventory management equipment		**20**					**12.9**		
		20							
6. Exploration & Research		306		0			1723		
6.1 Science Instruments		**0**					**1423.2**		
Habitat lab equipment		0							
6.2 Field Equipment (tools, cameras, et		**205.5**					**143.95**		
Field package (camera, mass spec, v		180.5							
Portable Life Science Instrumentatior		25							
Drill		0							
6.3 Samples (cores, rocks, etc)		**0**					**0**		
6.4 Experiment/Monitoring Stations		**0**					**0**		
MET and seismic monitor		0							
6.5 Robots/ robotic rovers		**100**					**0**		
tele-operated/autonomous robots		100							
6.6 Field habitation (tents, bivaouc, …)		**0**					**155.5455**		
7. Waste & Waste Disposal		303		2			547		
7.1 Waste		**77.52456**					**445.5**		
human solid fecal waste		75.24							
other human waste (hair, nails, skin e		2.28456							
7.2 Waste management equipment		**225.72**					**101.4**		
trash bags		34.2	0.001	0.684					
waste collection system supplies		34.2	0.0013	0.8892					
contingency waste collection supplies		157.32	0.0008	0.5472					
8. Habitation and Infrastructure		7060		5			1022		
8.1 Power systems and support equipn		**60**					**78.1**		
Power Plant		60							
8.2 Thermal management and support		**0**					**183.2**		
8.3 Life support, air pressure managem		**0**					**169.7**		
8.4 Structural containment, fasteners, a		**7000**					**478.5**		
Habitat and Lab Modules		7000							
8.5 ISRU plants and support equipment		**0**					**6**		
8.6 Construction equipment and tools (		**0**					**106.5**		
9. Transportation and Carriers		9600					9305		
9.1 ATV's, rovers, and support equipme		**6600**					**4281**		
All Terrain Vehicles		6600	4.9	4.9					
9.2 Pressurized rovers and support equ		**3000**					**5024.1**		
Pressurized Surface Vehicles		3000							
9.3 Logistics carriers & containers (crat		**0**					**0**		
10. Miscellaneous		50					102.1		
10.1 Public affairs and outreach (flags,		**50**					**73.6**		
10.2 Miscellaneous items		**0**					**28.5**		
Total		**23740**					**20717**		

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Appendix E: Exploration Logistics Use Cases and Database

Table E.1: Exploration Logistics Use Cases

Users	Required Information		
Astronauts			
•What, where are my next … days worth of meals?	location	quantity in stock	consumption rate
•When will the next perishable spoil?	current date	expiration date	
•Where is …?	location		
What are the physical properties of …? (size, mass)	size	mass	
•How long till … runs out?	quantity in stock	consumption rate	
What am I running {low, out} of?	quantity in stock	consumption rate	
•How long until I can get more X?	delivery schedule	priority level	
•What is the projected amount of … over … time period?	qunatity in stock	consumption rate	re-supply/delivery sc
–At highest, nominal, lowest consumption rates			
What is in storage area …?	location		
How much unused capacity is in storage area …?	item size	storage area size	
Mission Operators			
•Do the astronauts have what they will need at a given point in time?	quantity in stock	consumption rate	resupply rate
–What don't they have?	failure rate	spares	item info
•What's the "best" way to get it to them?	carrier info	origin	destination
–fastest, cheapest, …			
How long will it take to get … to the astronauts?	origin	destination	carrier
•What is the next launch opportunity for carrier …?	origin	destination	carrier info
What is the next available carrier?	priority level	delivery schedule	
What's the quantity on-hand and quantity due-in at each location (node	quantity in stock	delivery schedule	quantity in each deliv
•What will be my inventory at each location x days from now?	quantity in stock	delivery schedule	quantity in each deliv
Of my due-ins, how many are from procurement, in-repair on the ground (intermediate- and depot-level), en-route out, en-route back, failed in place.	item status	consumption rate	failure rate
Load Masters			
•What needs to go?	priority level	carrier	
•How much capacity does carrier … have, as a function of	carrier info	item info (size, mass)	
•What are the mass properties of …?	mass		
What are the physical dimensions of …?	size		
•What environments can … tolerate?	storage environment		
–Thermal, pressure, static & dynamic loads			
What are the mass properties of … manifest given the following packaging plan?			
Vendors/Procurers			
•What is needed?	quantity in stock	consumption rate	failure rate, spares
•When is it needed?	quantity in stock	consumption rate	failure rate, spares
•Where do I transfer it to you?			
What mode of ground transport?	ground transport info		
•How much will it cost?			
Where is it now?	location status		
•When will it get to its next destination?	current carrier info		
–Earliest, most likely, latest			
Logistics Modelers			
•What the projected consumption/failure rate over the next period?	number of crew/users	consumption/failure rates	
What's my system availability?			
•How should I allocate my fixed spares budget?	priority level	carrier info	origin, destimation

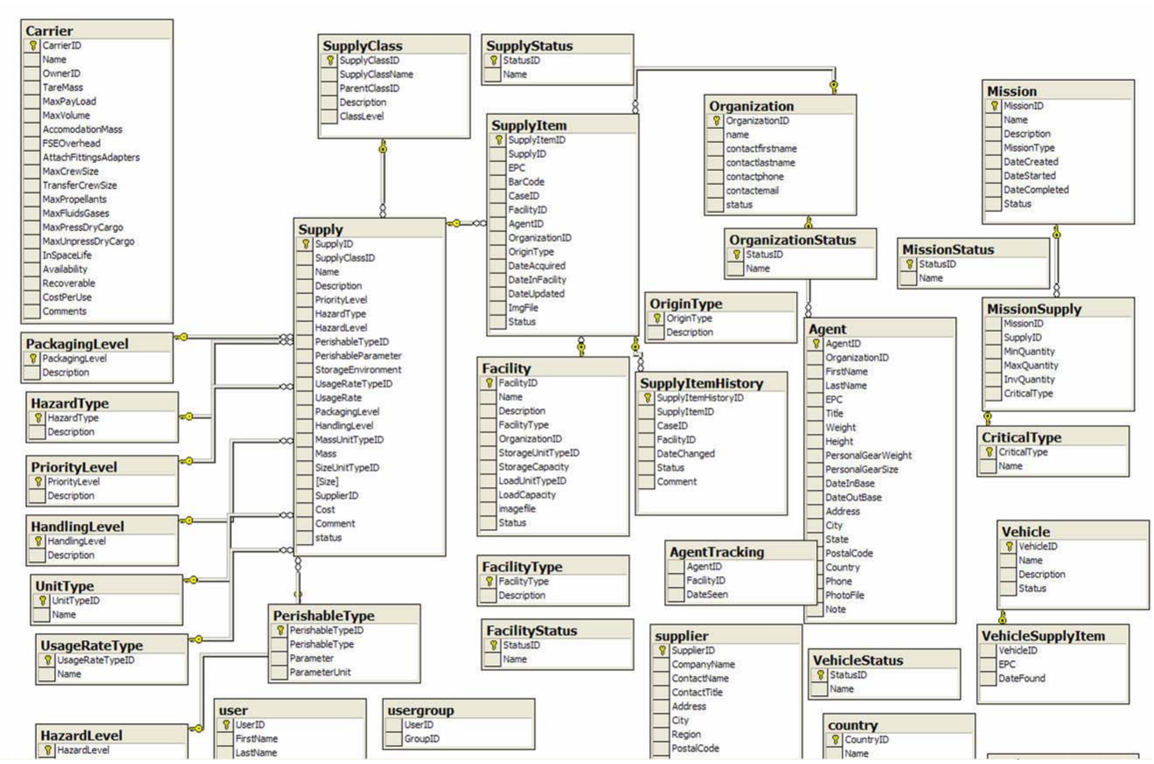

Figure E.1: Expanded Database Structure for Asset Tracking

Appendix F: Detailed HMP Flight Log

Table F.1: Summary of Flight log for HMP Logistics 2005

		Day #	# of FLTs	# of crew on base	# of crew in	# of crew out
8-Jul	**Fri**	0		0	0	
9-Jul	**Sat**	1	1	0	1	1
10-Jul	**Sun**	2	4	15	15	
11-Jul	**Mon**	3		15	0	
12-Jul	**Tue**	4	2	17	2	
13-Jul	**Wed**	5		17	0	
14-Jul	**Thu**	6		17	0	
15-Jul	**Fri**	7	2	19	4	2
16-Jul	**Sat**	8		19	0	
17-Jul	**Sun**	9		19	0	
18-Jul	**Mon**	10	6	34	15	
19-Jul	**Tue**	11		34	0	
20-Jul	**Wed**	12		34	0	
21-Jul	**Thu**	13		34	0	
22-Jul	**Fri**	14	1	35	5	4
23-Jul	**Sat**	15	1	37	2	
24-Jul	**Sun**	16		41	4	
25-Jul	**Mon**	17	1	31	0	10
26-Jul	**Tue**	18	1	24	0	7
27-Jul	**Wed**	19	1	28	5	1
28-Jul	**Thu**	20		28	0	
29-Jul	**Fri**	21	1	22	0	6
30-Jul	**Sat**	22	1	26	4	
31-Jul	**Sun**	23		26	0	
1-Aug	**Mon**	24		26	0	
2-Aug	**Tue**	25	1	19	0	7
3-Aug	**Wed**	26		20	1	
4-Aug	**Thu**	27		20	0	
5-Aug	**Fri**	28	1	14	0	6
6-Aug	**Sat**	29		6	0	8
7-Aug	**Sun**	30		6	0	
8-Aug	**Mon**	31	1	0	0	6
9-Aug	**Tue**	32	2	0	0	
10-Aug	**Wed**	33		0	0	

Table F.2: Detailed Flight Log (flight-by-flight) for HMP 2005[50]

Legend

Team	**Abb.**
HMP core researchers and staffs	CORE
Canadian Space Agency (Greenhouse, Telemedicine)	CSA
Simon Fraser University (Communications, Computing)	SFU
Field Assistant	FAS
University of Aberdeen	UAB
Mars Institute Intern	MAI
Space Logistics (MIT)	MIT
Robotics and Automation (NASA): DAME	DAME
NASA HQ	NASA HQ
Hamilton Sundstrand (Spacesuit)	HS
NASA JSC	JSC
Flight Surgeon	FS
Education / Public Outreach / Media	PUB

Flight 0 (Reconnaissance Flight)		**7/10**
Passengers In	**Team**	**Weight (lbs)**
Steve Braham	CORE	**200**
Cargo In		
5 Drums Diesel		
CORE CARGO 1		**2000**
WEIGHT IN		**2200**
Passengers In	**Team**	**Weight**
Steve Braham (returned with same flight after initial reconnaissance)	CORE	**200**

Flight 1		**7/10**
Passengers	**Team**	**Weight**
John Schutt[51]	CORE	**1200**
AC Hitch	CORE	
John Ferris	FS	
Gordon Osinski	CSA	
Cargo		
2 radios		
2 hand pumps-fuel		
2 bung wrenches (fuel drums)		
1 Honda generator 2 kW		

[50] The mass numbers for passengers and cargo are in lbs (1 kg = 2.2 lbs) and are based on rough estimates and handwritten log notes, not on precise measurements. A rough measurement of cargo for each flight is carried out at the Polar Continental Shelf Project to ensure that the 2400-2800 lbs payload mass range per Twin Otter flight is not exceeded, but we found these measurements and their documentation to be rather ad hoc.

[51] The mass of each passenger, incl. personal gear is assumed to be 300 lbs throughout.

6 shotguns		
1 MSat phone		
2 Logan tents (toilet)		
1 camp box-(tools)		
cribbing-wooden blocks		
sink filler		
CORE CARGO 1		**1000**
WEIGHT IN		**2200**

Flight 2		**7/10**
Passengers	**Team**	**Weight**
Jack Brezina (Camp Cook)	CORE	**900**
Alain Berinstain	CSA	
Tom Graham	CSA	
Cargo		
3 silver boxes SFr satellite phone		
frozen food (1/2 load)		
dry food food		
wet food		
produce		
paper towels		
CORE CARGO 2		**1000**
WEIGHT IN		**1900**

Flight 3		**7/10**
Passengers In	**Team**	**Weight**
Steve Braham	CORE	**900**
Christy Pires	SFU	
Hans Johnson	SFU	
Cargo In		
SFU satellite communications gear		
CORE CARGO 3		**1000**
WEIGHT IN		**1900**

Flight 4		**7/10**
Passengers In	**Team**	**Weight**
Jean-Marc Comtois	CSA	**1500**
Matthew Bamsey	CSA	
Richard Giroux	CSA	
Olivier de Weck	MIT	
Erica Gralla	MIT	
Cargo In		
Greenhouse Materials		400
Medical kits (red, CSA)		300
frozen food (1/2 load)		150

MIT Tent frame, wood		500
CSA CARGO 1		**700**
CORE CARGO 4		**150**
WEIGHT IN		**2850**

Flight 5		**7/13**
Passengers In	**Team**	**Weight**
Mike Li	MIT	**600**
Matt Silver	MIT	
Cargo In		
Greenhouse Materials		
Wood for MIT Tent		
CSA CARGO 2		
MIT CARGO 2		
WEIGHT IN	**(estimate)**	**1500**

Flight 6		**7/13**
Passengers	**Team**	
None		
Cargo		
CRC boxes		100
Propane (3)		510
Food Box		1600
Frozen Food		200
CORE CARGO		**2410**
WEIGHT IN		**2410**

Flight 7		**7/15**
Passengers In	**Team**	**Weight**
Shannon Pudluk	FAS	**600**
Richard Leveille	CSA	
Cargo In	**Number**	**Weight**
Greenhouse Batteries	35	2450
CSA CARGO 3		
WEIGHT IN		**3050**
Passengers Out	**Team**	**Weight**
Olivier de Weck	MIT	**600**
Erica Gralla	MIT	
Cargo Out		
Empty Long Propane Tanks	~10	600
CARGOOUT		**600**
Cargo Out		**1200**

Flight 8		**7/15**
Passengers In	**Team**	**Weight**
Connie Pudluk	FAS	**600**
Samson Simeone	FAS	
Cargo In	**Number**	**Weight**
Plywood for MIT tent tables	~10	
Plywood boards for MIT tent tables	5	
CSA Tent Cover	1	
Door for CSA tent	1	
Metal Cylinders for CSA tent	2	7lbs ea.
Metal Cylinders for CSA tent	2	15lbs ea.
Propane	1	180
MIT CARGO 3		**300**
CSA CARGO 4		**700**
CORE CARGO		**170**
WEIGHT IN		**1770**

Flight 9		**7/18**
Passengers In	**Team**	**600**
Kiel Davis	DAME	
Gale Paulsen	DAME	
Cargo In	**Number**	**Weight**
Rest of Dried Food For the Season	37 boxes total	300lbs
Frozen Food	1 big box	50 lbs
Communications Equipment Box: L band transceiver, C-band up commuter block, cables	2	
CORE CARGO 5		**1500**
WEIGHT IN		**2100**

Flight 10		**7/18**
Passengers In	**Team**	**Weight**
Howard Cannon	DAME	**600**
Edward Balaban	DAME	
Cargo In	**Number**	**Weight**
Weather Station		
Big Drill Box	1	
Drill Box	1	
Plywood for office tent backing	6	
CORE CARGO 6		**400**
DAME CARGO 1		**400**
WEIGHT IN		**1400**

Flight 11		**7/18**
Passengers In	**Team**	**Weight**
Marc Boucher	PUB	300
Brian Glass	DAME	300
Sathya Hanagud	DAME	300
Vinod Sharma	DAME	300
Agnivesh Tomar	DAME	300
Rhoda Akeeagok	FAS	300
Cargo In	**Number**	**Weight**
Drill Boxes	3	300
Pelican Boxes	2	200
WEIGHT IN		**2300**

Flight 12		**7/18**
Passengers In	**Team**	
Patrick Audlaluk	FAS	300
Hans Thater	PLA	300
Cargo In	**Number**	**Weight**
5 plastic tables		
lexan for greenhouse		
Science Instruments		
Kimmick (DOG)		
Propane	6	1040
WEIGHT IN		**1640**

Flight 13		**7/18**
Passengers In	**Team**	
None		
Cargo In	**Number**	**Weight**
Large Propane Bottles	2	360
CSA Tent		
CSA Tent Poles		
Tarp for CSA Tent		
PVC Piping for CSA Camera Cable		
Large Pelican Box with Instruments		
Pelican Box with Georgia Tech Gear	2	
Pelican Box with Georgia Tech Gear	1	
Georgia Tech Cylanders	2	
Cardoard Box with GT Instruments	1	
Propane	4	680
WEIGHT IN	**(estimate)**	**2000**

Flight 14		**7/18**
Passengers In	**Team**	
Pascal Lee	COR	300
Karen McBride	NASA HQ	300
Cargo In	**Number**	**Weight**
Propane Tanks	1	180
Polaris ATV	2	1400
Tables for CSA GH	2	200
WEIGHT IN		**2380**

Flight 15		**7/22**
Passengers In	**Team**	
Sarah Shull	MIT	300
Jaemyung Ahn	MIT	300
Sophie Caro	MAI	300
Paula Lindgren	UAB	300
John Parnell	UAB	300
Cargo In	**Number**	**Weight**
Large Propane Tanks	2	360
Polaris ATV	1	700
WEIGHT IN		**2560**
Passengers Out	**Team**	
Karen McBride	NASA HQ	300
Shannon Pudluk	FAS	300
Hans Thater	PLA	300
Cargo Out		**900**

Flight 16		**7/23**
Passengers In		
Jeff Jones	FS	300
Mona Khannas	PUB	300
Cargo In	**Number**	**Weight**
Propane	8	1440
CSA Todes		200
WEIGHT IN		**2240**
Passengers Out	**Team**	
None		
Broken ATV		750
Cargo Out		**750**

Flight 17		**7/24**
Passengers In	**Team**	
Philip (D)	PUB	300
Dennie (D)	PUB	300
Cargo In	**Number**	**Weight**
Film Crew Crate	2	
Film Crew Crate	2	
Film Crew Crate	1	
Film Crew Crate	1	
WEIGHT IN	**(estimate)**	**2100**
Passengers Out		
None		
Cargo Out		**1200**
CSA Medical Cases	2	400
Urine Barrel	2	800

Flight 18		**7/24**
Passengers In	**Team**	
Edith (D)	PUB	300
Gary (D)	PUB	300
John Tierney (Not on the List)		300
Cargo In	**Number**	**Weight**
Personal Cargo only		
WEIGHT IN	**(estimate)**	**900**
Passengers Out		
None		
Cargo Out		**1600**
4 Urine Drums		1600

Helicopter (R->D 1.3 hr)	Cost 2064 (Can $)	**7/24, 7/25**
Passengers In (24-Jul-05)	**Team**	
Pilots 2		
Passengers Out (25-Jul-05)	**Team**	
Pilots 2		
Jean Marc, Comtois	CSA	300
John Ferris	FS	300
Cargo Out		**600**

Flight 19		7/25
Passengers In	**Team**	
None		
Cargo In	**Number**	**Weight**
Diesel	2	800
Film Crew Crate	2	500
ATV	1	750
ATV Tire	6	180
Dry Food		300
WEIGHT IN	**(estimate)**	**2530**
Passengers Out		
Mike Li (MIT)		300 ea
Matt Silver (MIT)		
Alain Berinstain (CSA)		
Matt Bamsey (CSA)		
Richard Giroux (CSA)		
Tom Graham (CSA)		
Richard Leveille (CSA)		
Sathya Hanagud (DAME)		
Cargo Out		**2400**

Flight 20		7/26
Passengers In	**Team**	
None		
Cargo In	**Number**	**Weight**
Diesel	4	1600
Gasoline	2	800
WEIGHT IN	**(estimate)**	**2400**
Passengers Out	**Team**	
Howard Cannon	DAME	300 ea
Edward Balaban	DAME	
Kiel Davis	DAME	
Gale Calhoun	DAME	
Vinod Sharma	DAME	
Agnivesh Tomar	DAME	
Gordon Osinski	CSA	
Cargo Out		**2100**
Empty Propane (did not record exact number of bottles)		

Flight 21		**7/27**
Passengers In	**Team**	
Jessica Marquez	MIT	300
Julie Arnold	MIT	300
Gregory Quinn	HS	300
Susie Shimamoto	HS	300
Vicky Glass	CORE	300
Cargo In	**Number**	**Weight**
DIESEL	2	800
SPACE SUIT		310
WEIGHT IN	**(estimate)**	**2610**
Passengers Out	**Team**	
Connie Pudluk	FAS	300
John Tierney (Not in the List)		300
Cargo Out	**(estimate)**	**2100**
Waste		
Honeybee Drilling Facility		

Flight 22		**7/29**
Passengers In	**Team**	
None		
Cargo In	**Number**	**Weight**
None		
WEIGHT IN		**0**
Passengers Out	**Team**	**Weight**
Jaemyung Ahn	MIT	1800
Paula Lindgren	UAB	
Jeff Jones	PUB	
Mona Khanna	PUB	
Brian Glass	DAME	
Marc Boucher	PUB	
Cargo Out		**1800**
None		0

Flight 23		**7/30**
Passengers In	**Team**	
Jeff Hoffman	MIT	1200
Mario Runco	JSC	
Steve Hart	FS	
Charles Mason	Public	
Cargo In	**Number**	**Weight**

None		
WEIGHT IN		**1200**
Passengers Out	**Team**	**Weight**
None		
Cargo Out		**2470**
Urine Drum	1	400
Empty Gas Drums	2	800 (?)
Propane	1	70
Diesel Drums	2	800 (?)
Kawasaki ATV (small)	1	400

Flight 24		**8/3**
Passengers In	**Team**	
None		
Cargo In	**Number**	**Weight**
None		
WEIGHT IN		**0**
Passengers Out	**Team**	**Weight**
Sarah Shull		300 ea.
John Parnell		
Edith (D)		
Gary (D)		
Philip (D)		
Dennie (D)		
Pascal Lee (Flown to Griese Fiord for a meeting)		
Cargo Out		**2100**
Discovery Canada Film Equipment		
Flight 24a (No Cost)		**8/4**
Passengers In	**Team**	
Pascal Lee		
Cargo In/Out	**Number**	**Weight**
None		

Flight 25		**8/5**
Passengers In	**Team**	
Cargo In	**Number**	**Weight**
propane tanks (full)	2	360
diesel barrel	3	1200
gasoline barrel	1	400
wood door	1	150
food box	3	200
generator (CSA)	1	100
WEIGHT IN		**2410**

Passengers Out	Team	Weight
Julie Arnold	MIT	300 ea
Gregory Quinn	HS	
Susie Shimamoto	HS	
Vicky Glass	CORE	
Sophie	U. Paris	
Gordon	HSU	
Cargo Out		**2185**
Hamilton Sundstrand boxes (spacesuit)	2	315 lbs
trash bags (filled)		70 lbs

Flight 26		**8/3**
Passengers In	**Team**	
none		
Cargo In	**Number**	**Weight**
none		
WEIGHT IN		**0**
Passengers Out	**Team**	**Weight**
Jessica Marquez	MIT	300 ea
Jeff Hoffman	MIT	
Jack	CORE	
Steve Hart	JSC	
Rhoda	CORE	
Mario Runko	JSC	
Charles Mason	Morehead	
Hans Johnson	SFU	
Cargo Out		**2625**
propane tanks (empty)	2	100
trimble GPS equipment	2	50
dell laptops, pelikans	2	
HUMVEE radio	1	
access points	2	75

Flight 27		**8/7**
Log Not Available		
Cargo Out	**(estimate)**	**2000**

Flight 28		**8/7**
Log Not Available		
Cargo Out	**(estimate)**	**2000**

Appendix G: EVA Logistics Assessment Form

Table G.1: "EVA Log"

Excursion [NAME & DATE]	
Pre-Excursion Information: Purpose of EVA: Total Time: Participants: Number of sites visited: • Mobility to/from • Distance (absolute and path) • Estimated time in between Inventory Planning Environmental factors affecting excursion	*Post-Excursion Information:* Total Time: Number of sites visited: Unexpected events (re-planning):

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Appendix H: Details of Planetary EVA Parameters and Constraints

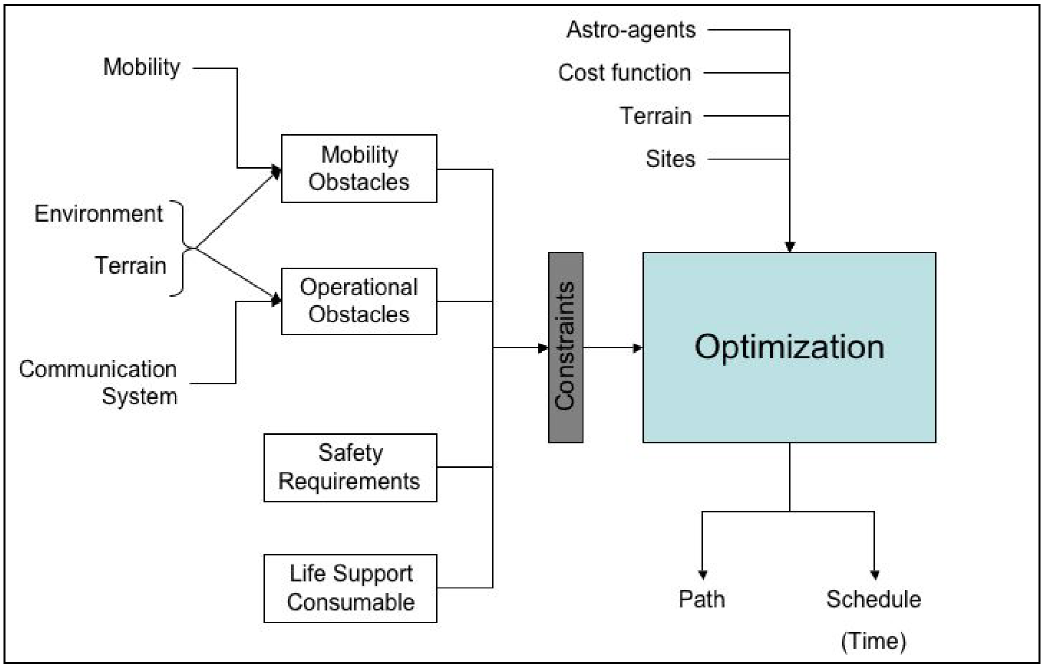

Figure H.1: Planetary EVA, parameters and constraints – overview

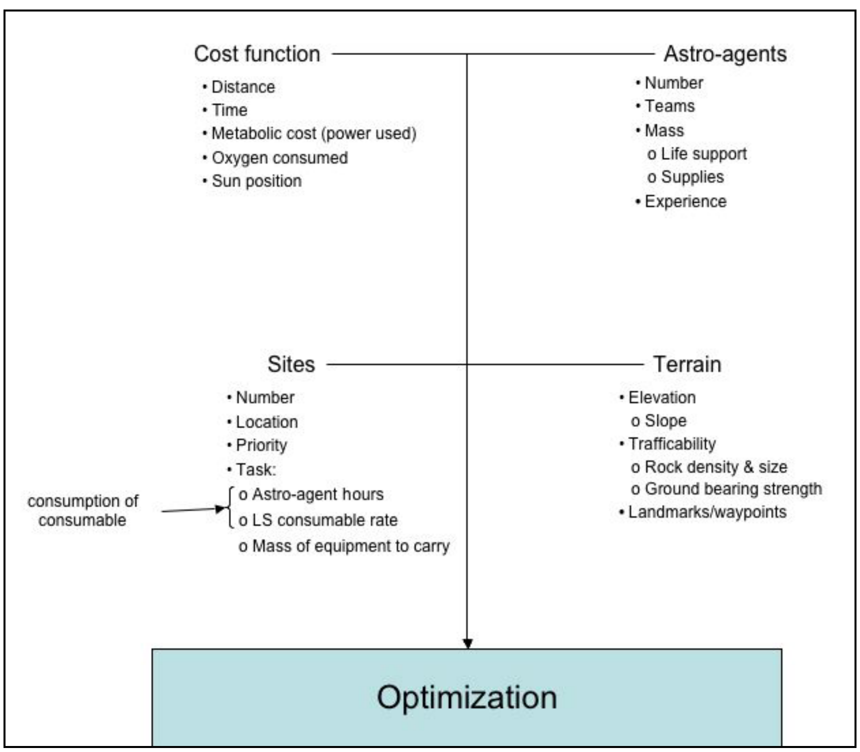

Figure H.2: Planetary EVA, Optimization Inputs

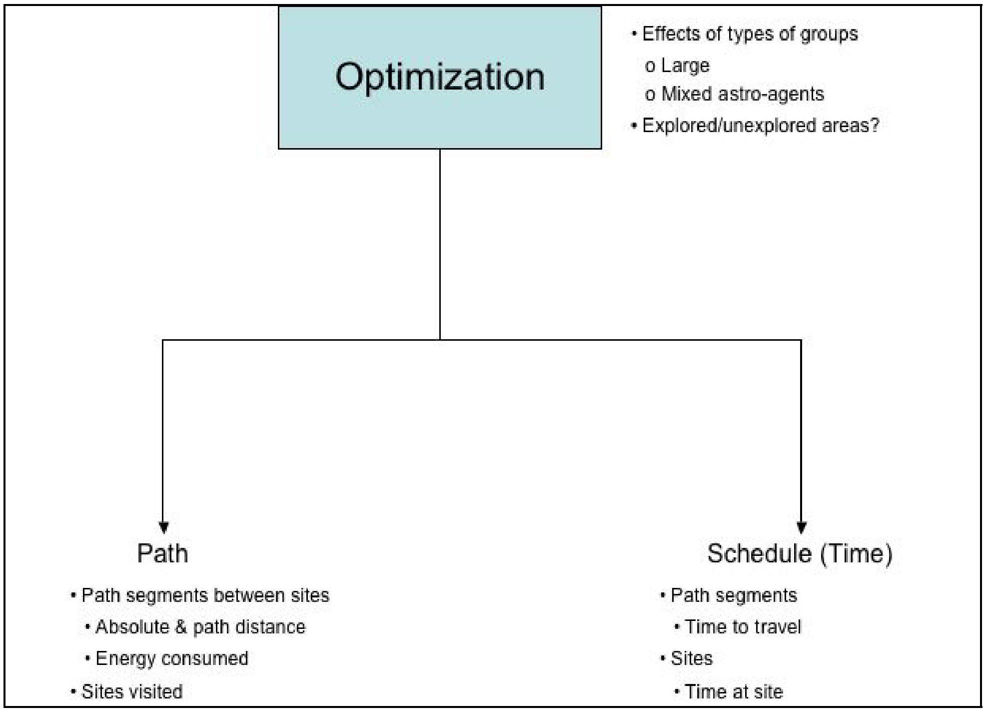

Figure H.3: Planetary EVA, Optimization Outputs

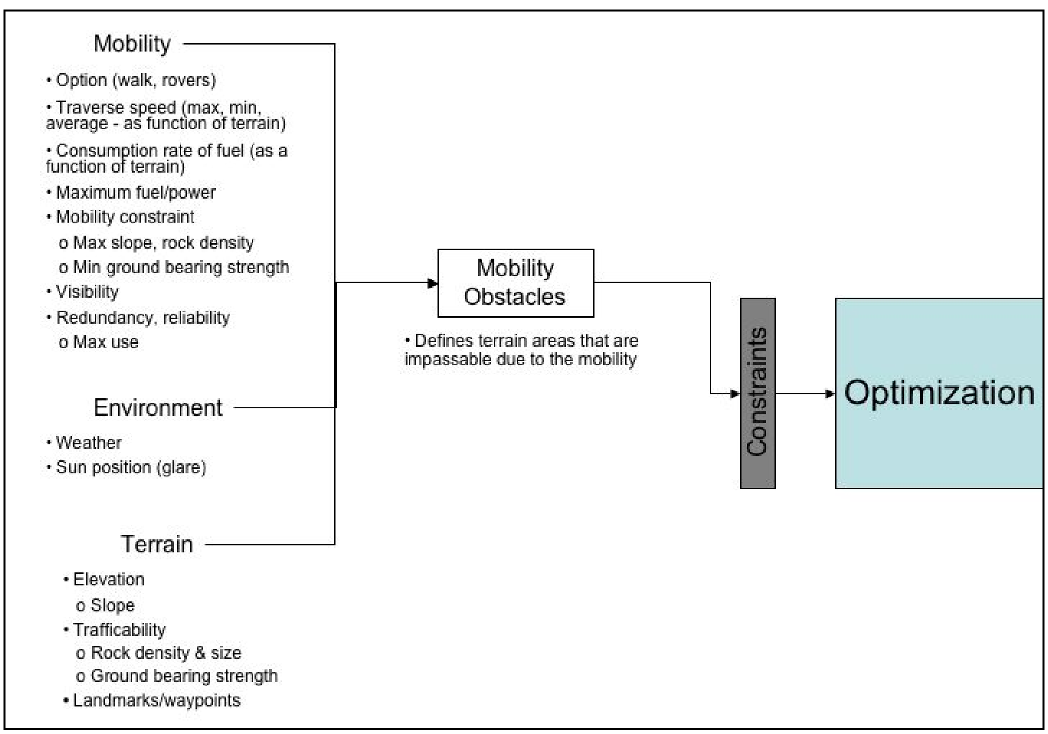

Figure H.4: Planetary EVA Optimization: Mobility Constraints

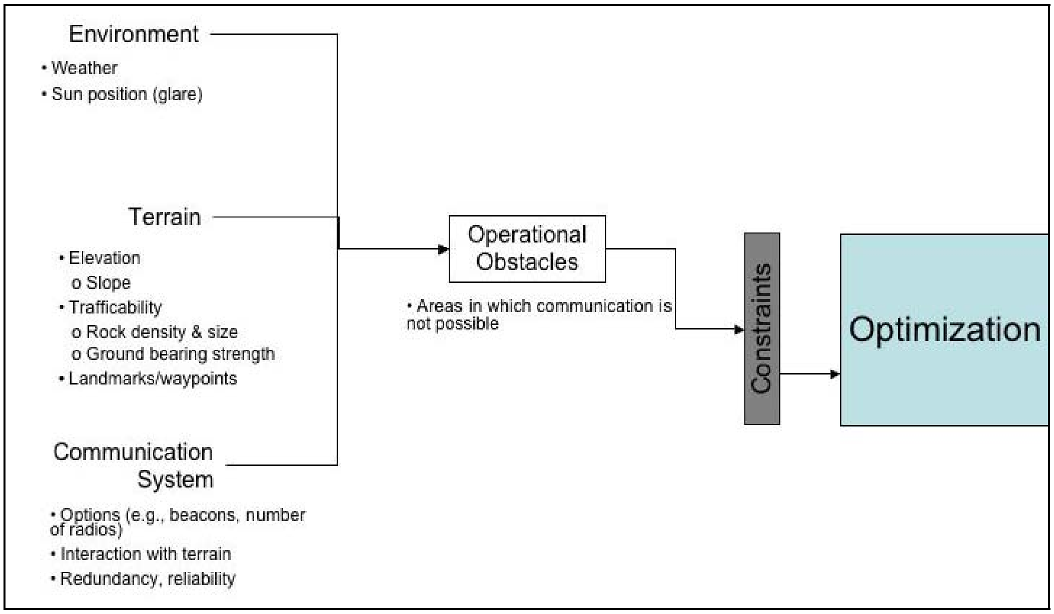

Figure H.5: Planetary EVA Optimization: Operational Constraints

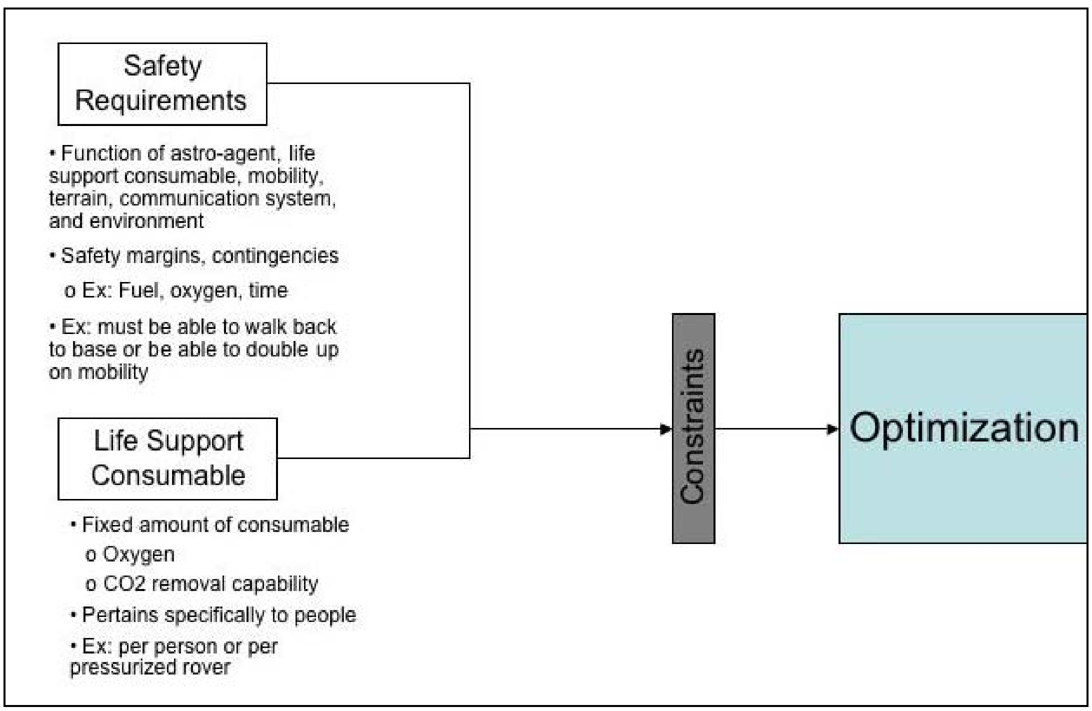

Figure H.6: Planetary EVA Optimization: Safety and Life Support Constraints

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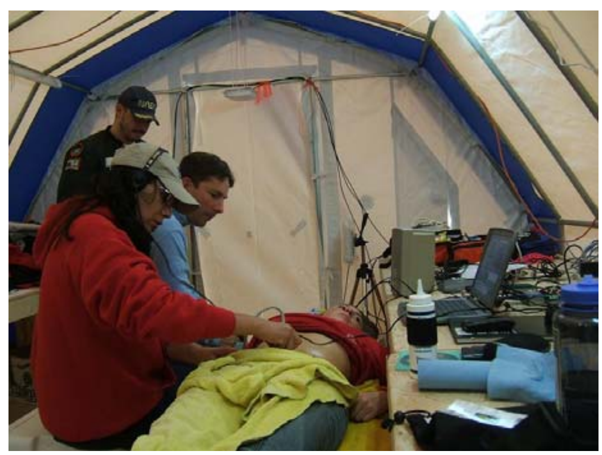
Appendix I: Selected Images

Inventory and Construction Activities at the HMP Research Station

left, top: HMP octagonal core structure
left, middle: recording inventory (E. Gralla)
left, bottom: inventory of office tent
right, top: construction of MIT tent (O. de Weck)
right, bottom: loading of liquid waste at HMP

Research and Maintenance Activities at the HMP Research Station



left, top: RFID ATV Tracking (M. Silver)
left, middle: RFID indoor programming
(E. Gralla, M. Li, M. Silver)
left, bottom: Autonomous Drill (NASA DAME)
right, top: Installing tracks on the Humvee
right, bottom: CSA Telemedicine Experiment

Transportation to and from HMP

left, top: Canadian North Charter at Resolute
left, middle: Twin Otter departing from HMP
left, bottom: Helicopter refueling at HMP
right, top: ATV’s ready (J. Ahn, S. Shull)
right, bottom: ATV’s on a traverse

Field Exploration in and around the Haughton Crater

left, top: Test of HSSS display (J. Hoffman)
left, middle: Measurements of surface features
left, bottom: Field test of HSSS spacesuit
right, top: Exploration at Discovery Bay
(J. Hoffman, P. Lee and M. Runco)
right, bottom: ATV in the field (P. Lee, Sasa)

Final Impressions

MIT graduate students Julie Arnold (top right), Jessica Marquez (bottom right), Jaemyung Ahn (bottom left) and Sarah Shull (upper left) with Von Braun Planitia in the background

Shatter Cone Rock Sample from the Haughton Crater

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Appendix J: Short Participant Biographies

Dr. Olivier de Weck: Assistant Professor, Principal Investigator **deweck@mit.edu**	Prof. de Weck is an assistant professor with dual appointments between the Dept. of Aeronautics and Astronautics and the Engineering Systems Division at MIT. His research focuses on strategic aspects of systems engineering, multidisciplinary design optimization and interplanetary supply chain management.
Dr. Jeffrey Hoffman: Professor of the Practice, Former Astronaut **jhoffma1@mit.edu**	Prof. Hoffman is a former NASA astronaut and has flown five Space Shuttle missions (STS 35, STS 46, STS 51-D, STS 61, STS 75) and has logged over 1000 hours in space. His research focuses on strategies and tools for effective Extravehicular Activities (EVA) and planetary surface operations on the Moon and Mars.
Jaemyung Ahn: MIT Graduate Student **jaemyung@mit.edu**	Jaemyung Ahn is a doctoral candidate at the MIT Dept. of Aeronautics & Astronautics. His undergraduate degree in Aerospace Engineering is from Seoul National University (South Korea). For several years he worked on the design and launch of sounding rockets at the Korean Aerospace Research Institute.
Julie Arnold: MIT Graduate Student **arnoldj@mit.edu**	Julie Arnold holds an undergraduate degree in Aeronautics & Astronautics from MIT. She has participated in the NASA Academy program in the past and is currently focusing on a taxonomy and optimization strategies for human and robotic interactions.
Erica Gralla: MIT Graduate Student **egralla@mit.edu**	Erica Gralla holds a bachelor of science degree from Princeton University and focuses her research efforts on logistics strategies for manned spaceflight and remote operations. For several years she has worked with JPL on developing a logistics planning and costing software for the International Space Station (Messoc).
Mike Li: MIT Research Scientist **mikeli@mit.edu**	Mike Li is a research scientist at the MIT Dept. of Civil and Environmental Engineering. His specialty is in software architecture and design in support of cutting edge logistics planning and RFID tracking technologies. He manages the MIT Supply Chain Forum, a consortium of over 20 companies in the area of supply chains.
Jessica Marquez: MIT Graduate Student **jjm@mit.edu**	Jessica Marquez is a graduate of Princeton University and is currently working on her doctorate at the MIT Dept. of Aeronautics and Astronautics, Man-Vehicle-Laboratory (MVL). Her research focuses on optimal EVA path planning and adaptive re-planning.
Sarah Shull: MIT Graduate Student **sshull@mit.edu**	Sarah Shull holds a degree in Aerospace Engineering from the University of Michigan. She is pursuing master's research in future information architectures for Space Exploration Logistics at MIT. She remains an employee of NASA JSC, where she was the Inventory Stowage Officer (ISO) for ISS for the past 4 years.
Matthew Silver: MIT Graduate Student **mrsilver@mit.edu**	Matthew Silver is a graduate of the International Space University and participated in his 2nd HMP expedition. In his first expedition (2003) he designed control systems for the Arthur C. Clarke Green-house. His research interests are in architectural lock-in for launch vehicles and distributed sensing for large Engineering Systems.

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